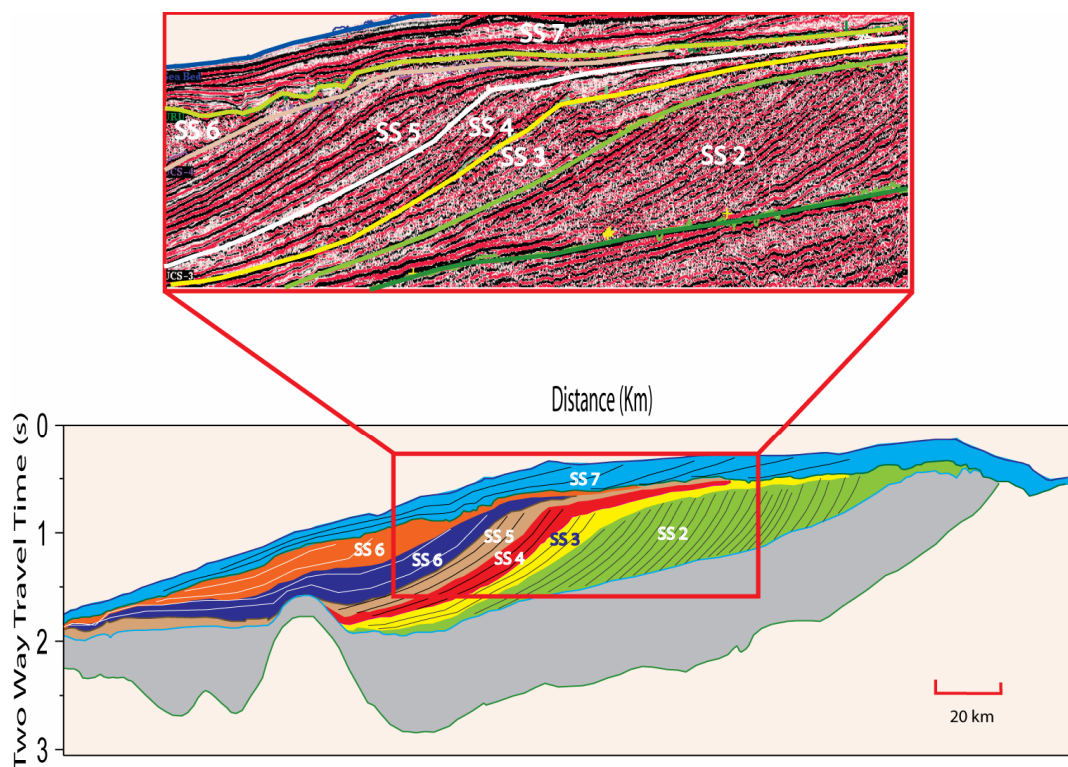


Master Thesis in Geosciences

Late Cenozoic Sedimentary Outbuilding Offshore Mid-Norway: Sequence Stratigraphic Analysis

by

Nadeem Abbas



UNIVERSITY OF OSLO

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

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Master Thesis in Geosciences

Discipline: Petroleum Geology and Geophysics

Department of Geosciences

Faculty of Mathematics and Natural Sciences

UNIVERSITY OF OSLO

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Tutor(s): Professor Johan Petter Nystuen and Professor Jan Inge Faleide

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Abstract

Cenozoic sedimentary successions along the passive continental margins of the Atlantic Ocean are of central importance in petroleum exploration. The aim of the present study has been to improve the understanding of the dynamics of the Plio-Pleistocene depositional system of the mid-Norwegian continental shelf. This study includes seismic stratigraphic interpretation of over 200 multi-channel 2D regional seismic lines followed by seismic sequence analysis and seismic facies analysis.

Seven seismic sequences together with five seismic facies have been identified and mapped regionally in an area ranging from 61° to 68°N, on the basis of reflector terminations and internal reflector configuration within CharismaTM. Three seismic surfaces including Local Downlap Surface (LDS), Regional Downlap Surface (RDS) and Upper Regional Unconformities (URU) are key surfaces mapped along with several internal unconformities in the study area. Chronostratigraphic charts (Wheeler diagrams) have been constructed along two selected seismic sections to obtain better insight into the time relationships of the depositional systems, and their relationships to surfaces of non-deposition, condensation and erosion.

On the basis of seismic sequence analysis the evolution of the Late Cenozoic sedimentary prograding wedge in the northern North Sea and off mid-Norway has been divided into three phases: (1) Initial phase marks the onset of sediment progradation with formation of sequence SS 1; (2) Main phase of large scale sediment outbuilding, SS 2 – SS 6; and (3) Final phase of regional erosion followed by aggradation in SS 7. The ages for the seismic surfaces have been adopted partly from earlier studies and partly assigned using relative age criteria, as there exist limited well and biostratigraphic data to give exact ages. Seismic sequence 1 seems similar to the Molo Formation in northern part of the study area and the Utsira Formation in the southern part of the study area both stratigraphically and geometrically, but the exact ages of these three correlated units are not known.

The Plio-Pleistocene prograding wedge succession in offshore mid-Norway is interpreted as the response of a complex interplay between a set of diverse controls: tectonic tilting and climate; sediment supply, primarily glacially derived; sediment transport mechanisms involving downslope and alongslope current activity; and deep and shallow water erosional and depositional processes.

Preface

This thesis has been carried out as a joint work with my colleague Mohammad Najibur Rahman at the Department of Geoscience, University of Oslo under the supervision of Professor Johan Petter Nystuen and Professor Jan Inge Faleide. I owe a special thank to Johan Petter Nystuen for his constant support, constructive comments, encouragement, very interesting discussions, and for always being optimistic on my behalf. I am very grateful to Jan Inge Faleide for advice, valuable guidance and inspiring ideas for seismic stratigraphic interpretation. I thank Dr. Michel Heeremans for his continuous collaboration and technical support for Geoframe Software during the seismic interpretation phase of this project.

TGS-NOPEC and WesternGeco are acknowledged for contributing to the seismic database. At the same time I acknowledge Norwegian State Education Loan Fund (Lånekassen) for financing not only my thesis but also entire master program as a Quota Student at University of Oslo.

I would like to express my gratitude to my thesis project fellow Mohammad Najibur Rahman for his continuous support, sharing ideas and interesting discussions throughout this study and also for being nice friend throughout the master program. Also thanks to my dear class fellow Olav Antonio Blaich for introducing me to the Adobe Illustrator and guiding me throughout master thesis. Abdu, Abbas Saeed Farah, Vidar Johannessen, Thomas Bodin are thanked for being very nice fellows and friends and for providing opportunity to work with them.

In the end I would like to thank my parents for their invaluable encouragement throughout my educational career and special acknowledgement for Mian Mehmood Ahmed Pervaiz without whose logistic support it would have impossible for me to come up at present level. Special thank to friends of Uncle Aslam Awan the Dar family for being very nice hosts here in Norway.

It has been a pleasure learning geology in the cold winters and pleasant summers of Norway.

Nadeem Abbas
Oslo, June, 2006

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1. Introduction

Cenozoic sedimentary successions along the passive continental margins of the Atlantic Ocean are of central importance in petroleum exploration. The Cenozoic reveals great variation in thickness, facies and depositional style from Paleocene to Present, depending on regional and local structural framework and other factors controlling the sedimentary systems. Climate and tectonics influence sea level fluctuations as well as sediment dispersal and depositional architecture. By the onset of glaciations in late Neogene time, climate became a dominant factor in the evolution of the shelf areas. This is particularly evident on high latitudes, as along the Norwegian shelf towards the Norwegian Sea. In addition, Scandinavia was the site of tectonic uplifts in the late Cenozoic. The Norwegian continental shelf successions are thus a prominent record of the combined effects of climate in glacial periods and tectonics.

The Norwegian continental shelf between 62°N and 69°30'N became the area of massive sedimentary outbuilding during late Cenozoic time. This part of the shelf is thus particularly suited for studies of the climate-tectonics interaction concept. This Plio-Pleistocene sedimentary succession is generally considered to be glacially driven prograding wedges formed by westwards transportation of glacial and glacio-fluvial sediments from mainland Norway. A complex interplay between a set of diverse controlling factors, such as tectonics and tilting (uplift and subsidence), climate, sediment supply from a variety of sources, and sediment transport mechanisms is responsible for the development of such large scale sediment progradation on the mid-Norwegian continental margin.

The object of the present master thesis project has been to improve the understanding of the dynamics of the Plio-Pleistocene depositional system of the mid-Norwegian continental shelf (figure 1-1) as regards parameters influencing this depositional system. Particular attention has been paid to the sequence stratigraphical evolution of the late Cenozoic package with identification of regional important sequence boundaries, formed by subaerial or subglacial erosion, submarine unconformities, transgressive surfaces, maximum flooding surfaces and condensed intervals. Seismic mapping has been made in accompany with Mohammad Najibur Rahman, and the results of the seismic stratigraphic analysis in my study have been discussed together with the results of the basin analysis in the Master Thesis of Mohammad Najibur Rahman.

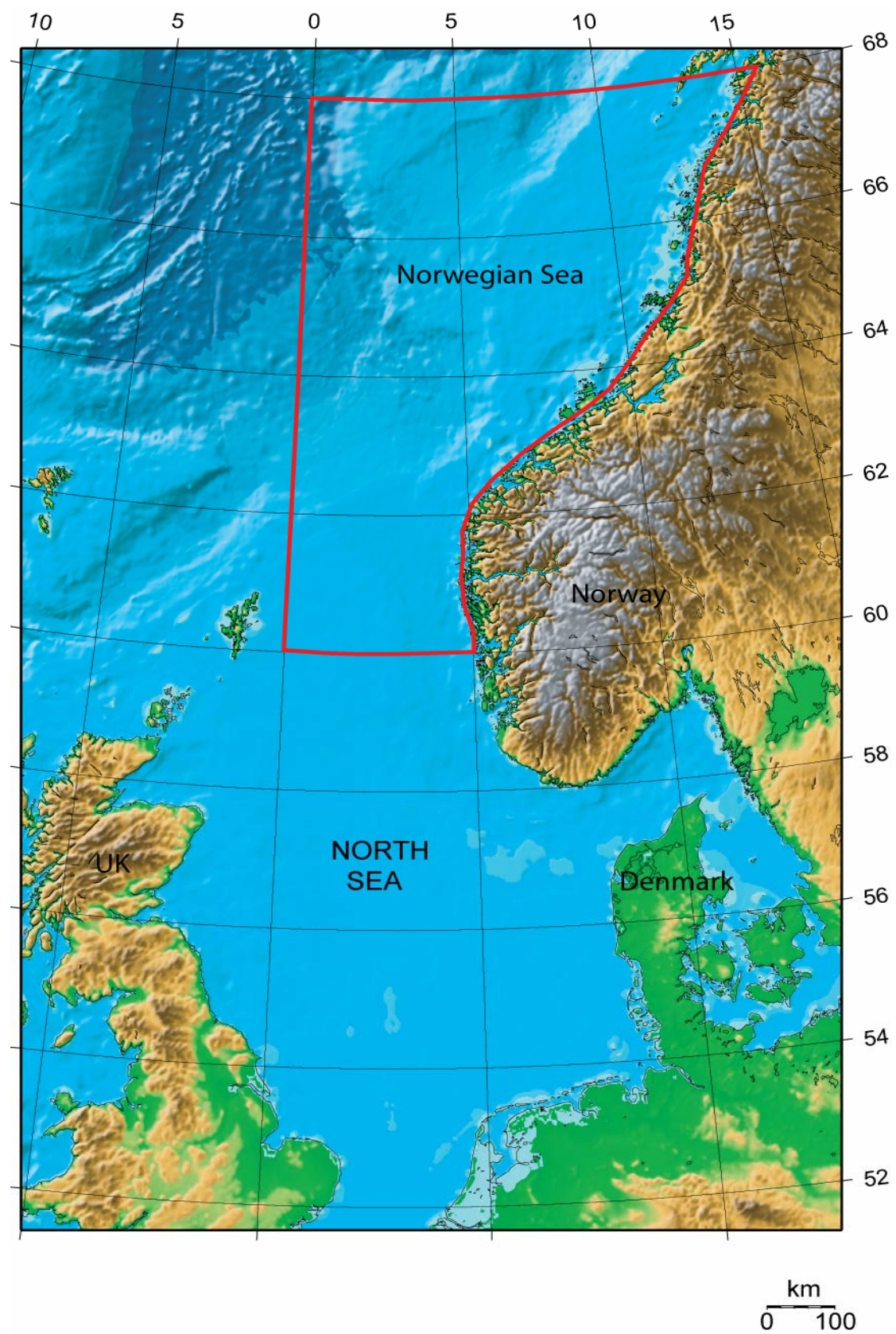


Figure 1-1: Regional setting and Location of the study area in the northern North Sea and mid Norwegian continental shelf.

2. Geological Framework

A description of the history of the North Atlantic margin, the main structures of the mid-Norway continental margin and its stratigraphy are presented here, providing a framework to understand the regional temporal and spatial development.

2.1. Structural Elements

The main structural elements on the Mid-Norwegian continental margin are the Trøndelag Platform, Møre Basin, Vøring Basin, Vestfjord Basin and Vøring Marginal High. The following presentation of the structural elements are based on (Blystad et al., 1995; Bukovics and Ziegler, 1985), if nothing else is mentioned.

2.1.1. Trøndelag Platform

The Trøndelag Platform is an up to 160 km wide area between the Norwegian mainland and the Vøring basin. The Revfallet Fault Complex in the NW, the Bremstein Fault Complex in the west and the Klakk Fault Complex in the south (Figure 2-1) bound the Trøndelag platform. In the east, crystalline basement outcrops at the sea floor along the coast. The platform area includes several structural elements like the Nordland Ridge, Helgeland Basin, Frøya High, Froan Basin and Ylvingen Fault Zone (Figure 2-1). The base Cretaceous level defines the platform, and the Cretaceous section rarely exceeds 500 m in thickness on the platform, except in the Helgeland Basin.

2.1.2. Møre Basin

The Møre Basin is bounded by Møre-Trøndelag Fault Zone in the east and Faeroe-Shetland Escarpment on west (Figure 2-1). To the south, Møre Basin shallows somewhat and grades into the Viking Basin of the northernmost North Sea. The northern limit of the Møre Basin is defined by a zone to the north of which Cretaceous and Tertiary strata were affected by partly steep reverse faulting and folding. Møre Basin contains intra basinal highs like the Nordfjord High and Vigra High.

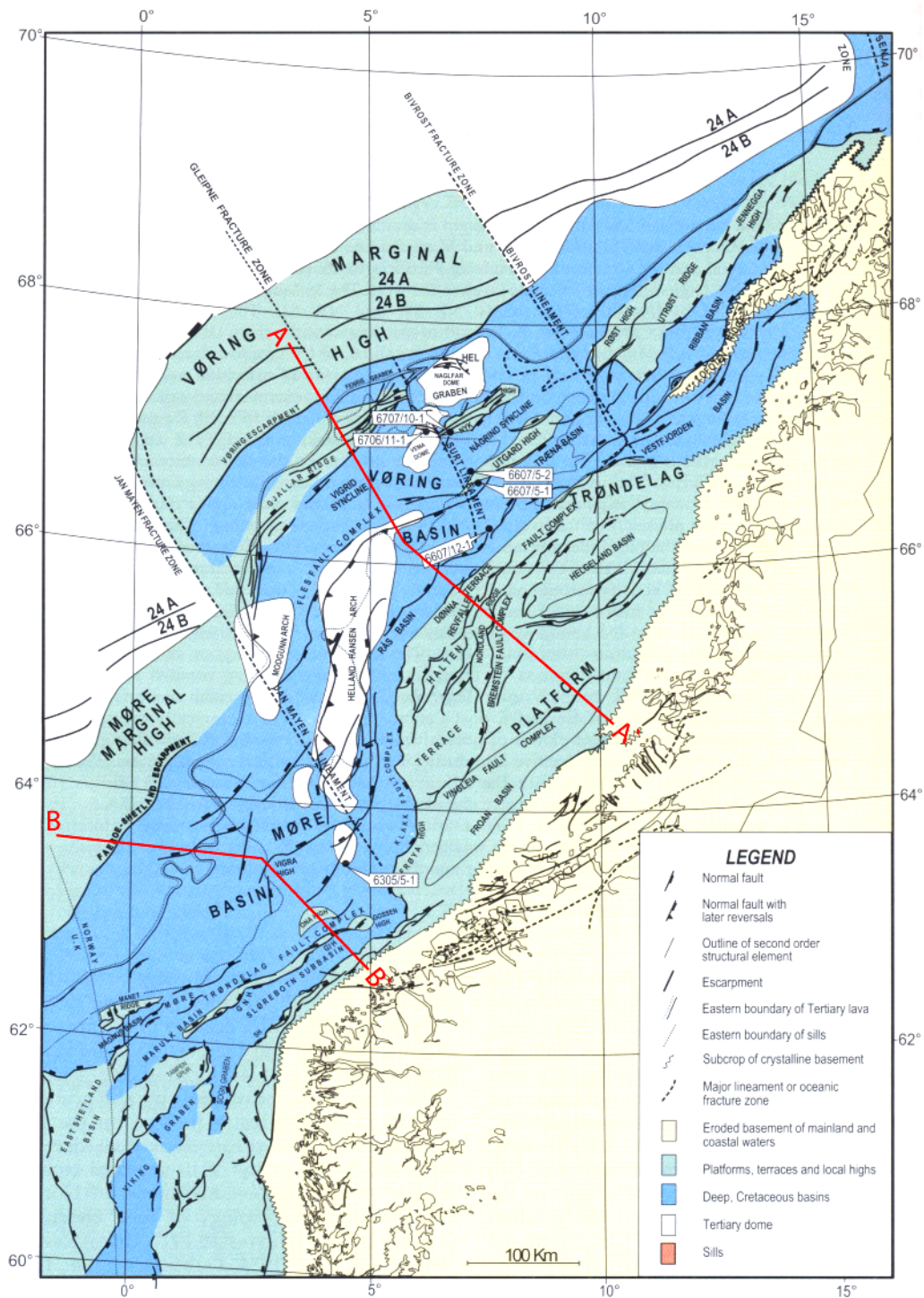


Figure 2-1: Simplified structural map of the Norwegian Sea continental margin. GIH, Giske High; GNH, Gnausen High; SH, Selje High (redrawn from Brekke, 2000).

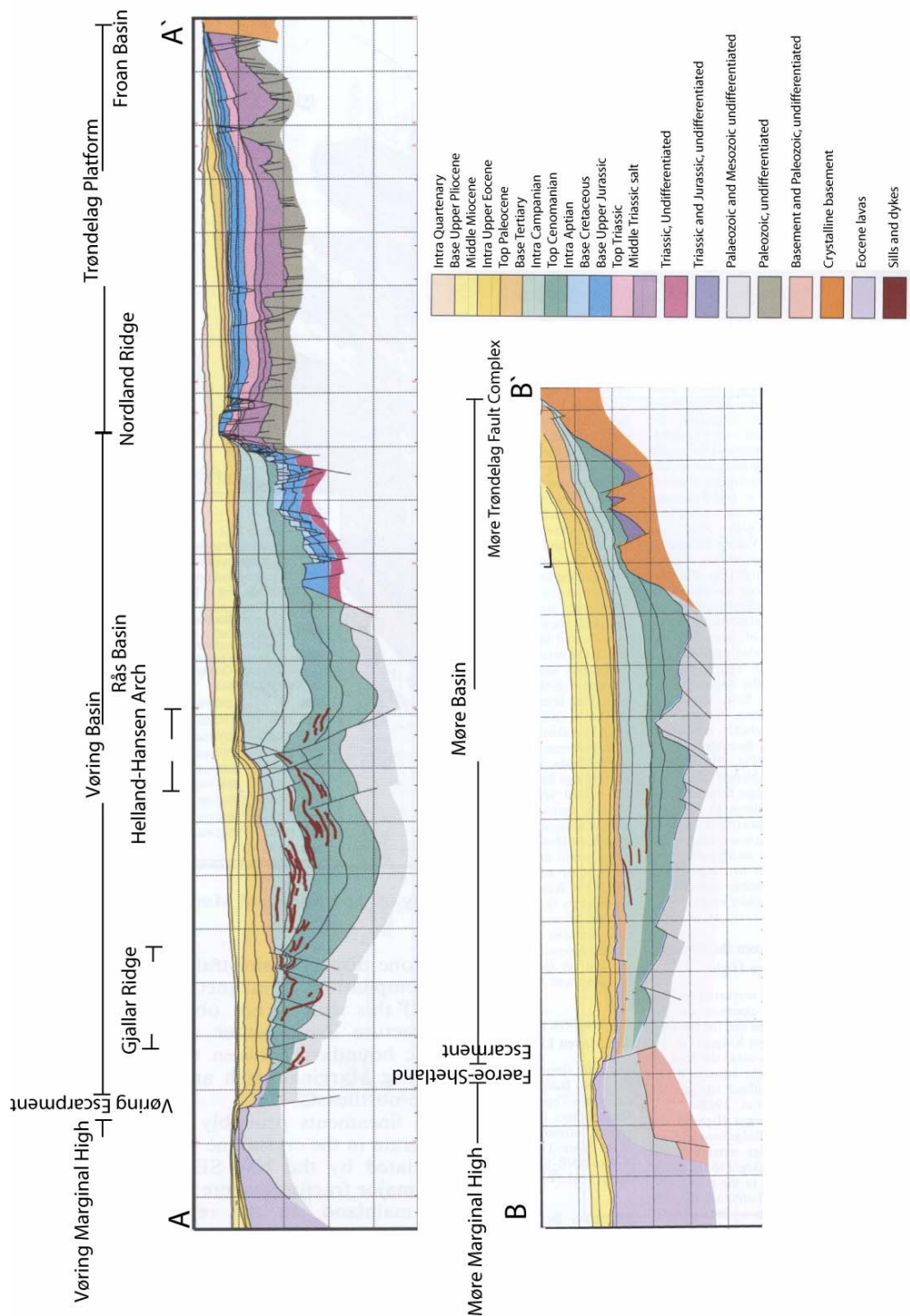


Figure 2-2: Geoseismic sections AA' and BB' (See Figure 2-1 for line location) showing main structural elements on Vøring Basin area (AA') and Møre Basin area (BB') (modified from Brekke, 2000).

2.1.3. The Møre Marginal High

The marginal high is situated to the west of the Faeroe-Shetland Escarpment and bounded to the north by Jan Mayen Fracture Zone (Figure 2-2). To the south, the Møre Marginal High merges with the Faeroe Plateau, which includes the Faeroe Islands (Brekke, 2000).

2.1.4. Vøring Basin

The Vøring Basin (64-68°N and 2-10°E) is a large sedimentary basin province with grabens, sub-basins and structural highs defined at the base Cretaceous level. It is bounded in the east by the Revfallet Fault Complex and the basement highs forming the extension of the Lofoten trend. The western and north-western boundary of the Vøring Basin is formed by the Vøring Plateau Escarpment (Figure 2-1 and 2-2) (Bukovics and Ziegler, 1985). The main structural elements of the Vøring Basin, as defined by the Base Cretaceous Unconformity level, are a series of high and low trends, with individual segments exhibiting a northerly to east-northeasterly strike. The trough shaped Vikna Graben and Træna Basin are located between the Nidaros Arch to the east and the Nykan and Molde High to the west.

Numerous sills of Late Cretaceous-Paleocene age have intruded the Vøring Basin and are observed east of the inner lavas flows and mask the seismic signature of the strata below. These features are associated with the continental separation and the onset of the sea floor spreading in the Norwegian Sea. Domes and arches, as for example the Helland-Hansen Arch and Modgunn Arch, represent Tertiary deformation, of the middle Eocene to Early Oligocene and Miocene age. The Helland-Hansen Arch is the most prominent of these features. Several mechanisms for the formation of these structures are suggested in the literature (Blystad et al., 1995; Bukovics et al., 1984).

2.1.5. Vestfjord Basin

Vestfjord Basin is located between the Lofoten and the Norwegian mainland and to the NE of the Træna Basin for which few data are available. The basin consists of a set of halfgrabens that contain mainly pre Jurassic sediments (Bukovics and Ziegler, 1985).

2.1.6. The Vøring Marginal High

The Vøring Marginal High is and bounded to the east by the Vøring Escarpment (Figure 2-2) and to the west and north by a zone of transition to normal oceanic crust, and its southern boundary is defined by the Jan Mayen Fracture Zone. On the inner high, there are sequences

of relatively flat-lying lavas above a presumably continental block, which is probably strongly intruded (Skogseid et al., 1992). The outer high is marked by thick units of seaward dipping reflectors representing a westward-thickening lava pile which represents partly upper part of an anomalously thick ocean crust.

2.1. Geological Development of the Mid Norway Continental Margin

The Norwegian Sea region of the Norwegian continental shelf comprises most of the continental margin between 62°N and 69°30'N. This part of the Norwegian continental margin may be described as a rifted passive continental margin. The tectonic development of the Norwegian Sea was more closely influenced by the break-up and formation of the North Atlantic in the Tertiary than other parts of the Norwegian continental shelf. Two major plate tectonic episodes, the Caledonian Orogeny and the break-up of the North Atlantic, divide the tectonic history of the area into three epochs: (Blystad et al., 1995)

- 1) The pre-Late Devonian epoch, this ended with the final closure of the Iapetus Ocean (Proto-Atlantic) during the Caledonian Orogeny in Late Silurian and Early Devonian time.
- 2) The Late Devonian to Palaeocene, a period of episodic extensional deformation culminating with the continental separation between Eurasia and Greenland at the Palaeocene-Eocene boundary.
- 3) The Earliest Eocene to Present, a period of active sea floor spreading between Eurasia and Greenland (Blystad et al., 1995) (Figure 2-3).

These epochs are further explained, subdivided into number of events and are briefly described under here.

2.1.1. Palaeozoic Development

Closing the Iapetus Ocean and collision of the Greenland-Laurentian and Baltic plates led to the Ordovician-Early Devonian Caledonian Orogeny. The Caledonian Orogeny collapsed during Early to Middle Devonian (Blystad et al., 1995). This stage was characterised by rapid erosion, which led to the creation of molasse basins. After the intense compressional phases associated with Caledonian suturing, deformation and strike slip displacement of Scandinavia and Greenland the proto-Atlantic rift evolution began in the late Palaeozoic.

From the early Late Carboniferous time onwards, the evolution of the area of the future Norwegian-Greenland Sea was dominated by regional crustal extension. This led to an

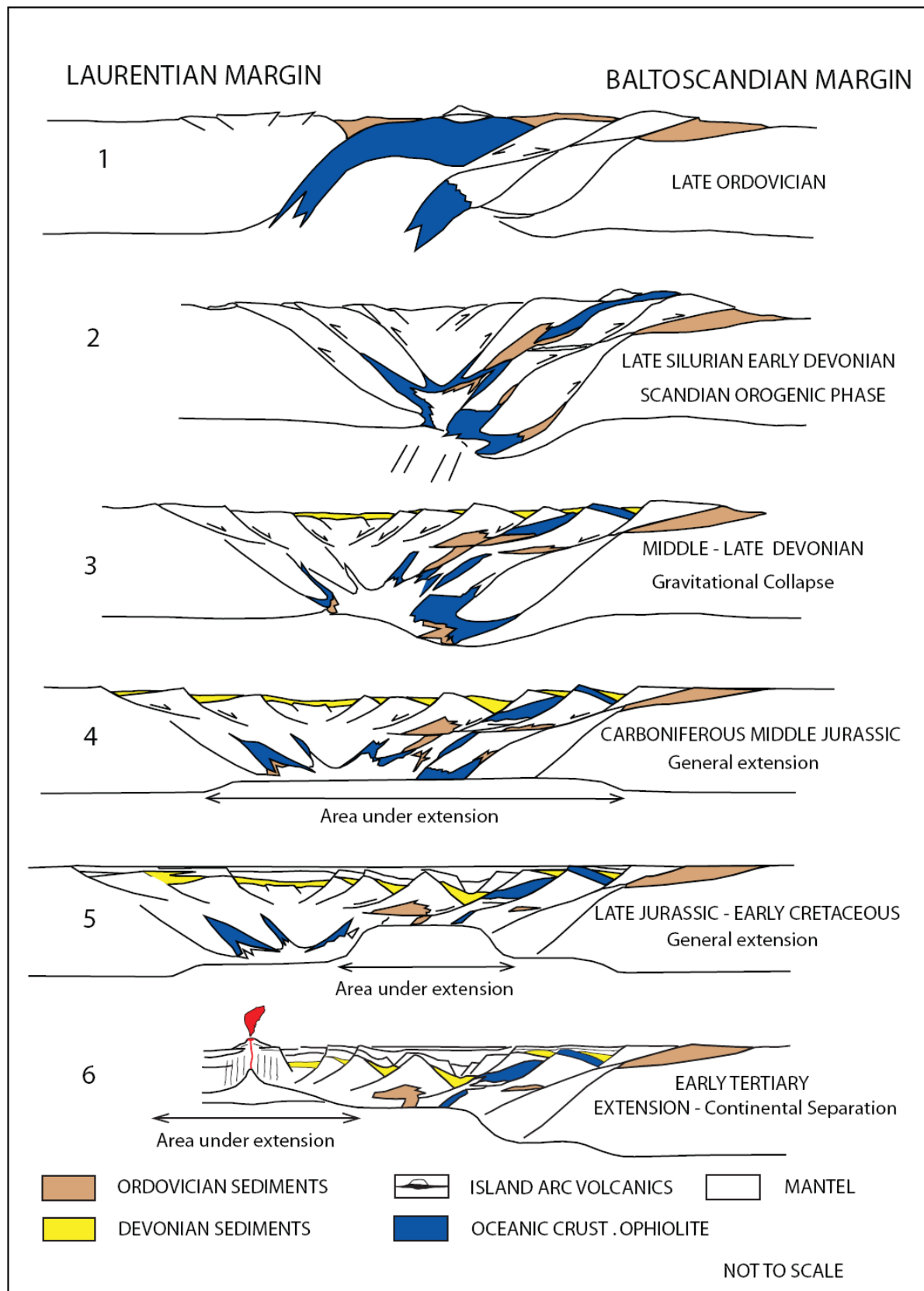


Figure 2-3: Schematic diagram illustrating an evolutionary model of the margin off mid-Norway from late Ordovician to early Tertiary time (redrawn from Skogseid et al., 1992)

extensive rift system which resulted in the deposition of Carboniferous and Permian clastic and carbonate sediments in half grabens that were bounded by listric, basement involved normal faults (Figure 2-3).

2.1.2. Mesozoic Development

Crustal extension persisted and accelerated during the Late Permian-Early Triassic rift phase (Figure 2-4). The rift activity accelerated at the transition to the Triassic in the incipient Norwegian-Greenland rift system. The Late Permian-Early Triassic rift phase at the Mid-Norwegian shelf, recognised in seismic data, is characterised by uplift, block faulting and erosion, which created basin range topography along the rift flanks. The typical Triassic configuration in most of the North Atlantic rift system is wide spread emergence and regression of the seas to the northern and southern extremity of the region, combined with rapid sediment accumulation caused by extensional faults (Doré, 1992).

The beginning of the late Permian was a time of transgression over most of the area. This event was marked by a change from restricted evaporitic and sabkha facies to more open marine depositional style (Worsley and Aga, 1986).

Early Mesozoic Rifting stage: Global sea level lowstand marks the early Triassic regression. In the Norwegian-Greenland sea area, crustal extension accelerated during early Triassic and extended towards North Sea (Ziegler, 1982). This resulted in the accumulation of substantial thickness of Triassic sediments, in the most subsiding areas (Knott et al., 1993). On the Trøndelag Platform and the Halten Terrace seismic data show evidence of syn-depositional Triassic and Jurassic listric faulting with rotation of the down thrown blocks. Compensatory antithetic faults gave rise to typical horst and graben structures.

Middle Triassic to Earliest Jurassic: During Middle Triassic to earliest Jurassic, an eustatic lowstand resulted mainly in the deposition of continental strata over the Halten Terrace and Trøndelag Platform (Whitley, 1992). This period was tectonically quiescent, except for minor uplift and faulting along the Nordland Ridge and Frøya High (Whitley, 1992).

Early Jurassic: in the Early Jurassic, a relatively minor tectonic phase resulted in down-to-the-west growth faulting throughout the Halten Terrace during which a delta front sand complex was deposited followed by marine transgression (Blystad et al., 1995).

Middle Jurassic: The overall transgressional trend of Early Jurassic continued in Middle Jurassic times but was disrupted by local regressions. Middle Jurassic was a time of tectonic quiescence during which marine and fluvial environments returned to the Trøndelag Platform and Haltenbanken area. This resulted in the deposition of the Fangst Group (Blystad et al., 1995; Whitley, 1992). There are widespread variations in the thickness of different units of this Group due to the influence of syn-sedimentary faulting and erosion associated with the Cimmerian fault movements.

The Fangst Group typically consists of (a) lower fine to medium grained sandstone with numerous shaly interbeds called Ile Formation (Figure 2-6), deposited in various tidally influenced delta or coastline setting, (b) a middle mudstone called Not Formation which reflects a semi-regional transgression which led to the development of lagoons or sheltered bays, whereas the upper part represents prograding deltaic or coastal front deposits, (c) an upper relatively massive fine to coarse grained sandstone called Garn Formation deposited by progradation of braided delta lobes; active fluvial and wave influenced sedimentary facies processes are also recognised. The Fangst Group is present in most of the Trænabanken – Haltenbanken area except on the highest parts of the Nordland Ridge where it has been eroded (Dalland et al., 1988).

Late Mesozoic rifting stage: As in the North Sea area, the late Kimmerian rifting pulse, at the transition from Jurassic to Cretaceous, strongly affected the Mid-Norway area (Bukovics and Ziegler, 1985). The Fangst Group was totally or particularly eroded on major highs during the early phases of this tectonic pulse. This resulted in the formation of a wide spread unconformity. This event was succeeded by a second major transgression beginning towards the end of the Middle Jurassic, producing marine shales, the Melke Formation. This marine transgression continued into Early Cretaceous resulting in the deposition of hydrocarbon rich source rock, the Spekk Formation, which unconformably overlies the Melke Formation. Intense northwest-southeast to east-west oriented regional extension began with the earliest Melke deposition and continued throughout the Early Cretaceous.

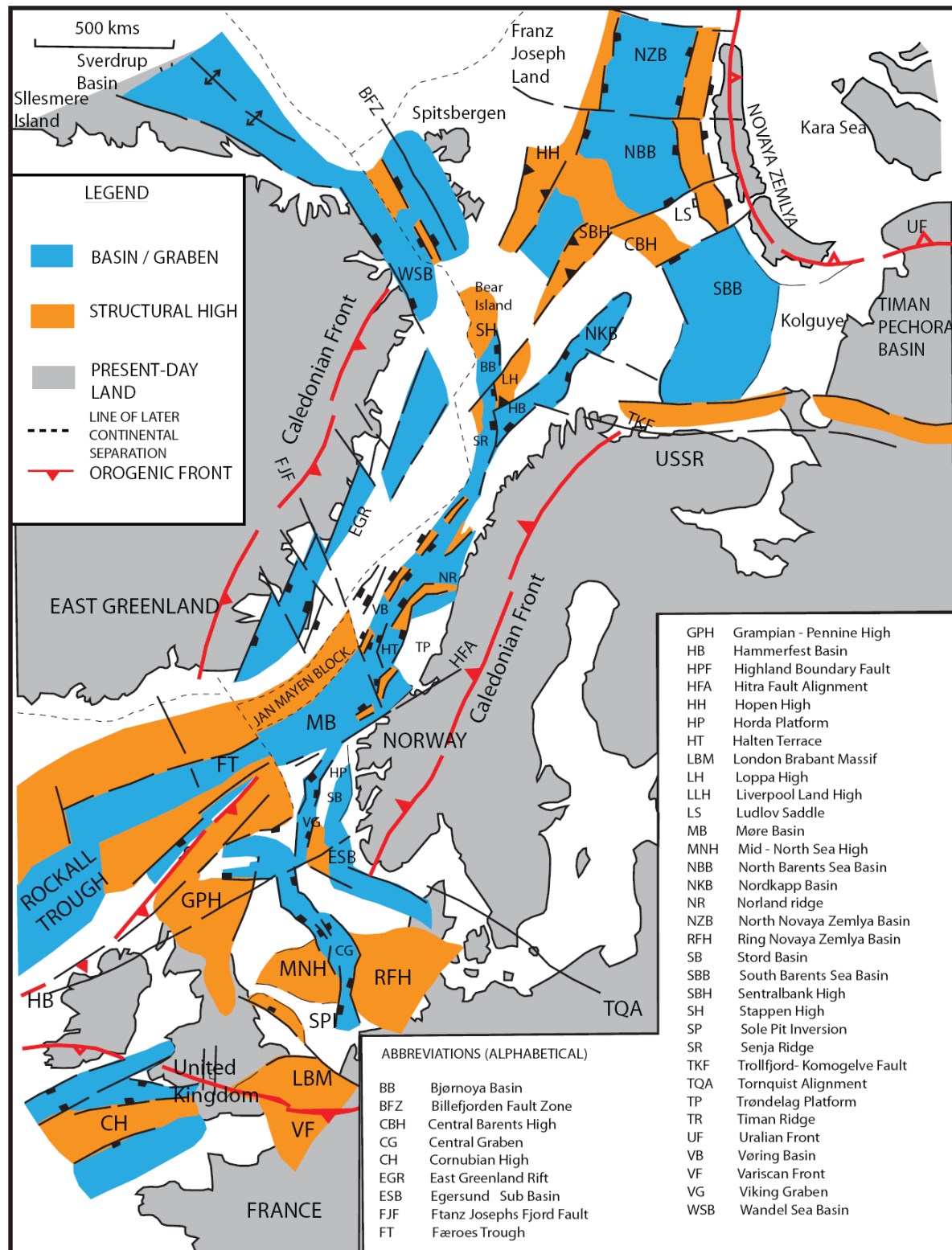


Figure 2-4: Principal Mesozoic structural elements of the North Atlantic and Barents Sea (redrawn from Dore, 1991).

This episode created the tilted fault blocks and horsts that contain most of the hydrocarbon accumulations of the Mid-Norwegian shelf. The Spekk Formation is remarkably persistent except for the islands at the top of the rotated fault blocks. This suggested that much of the

late Kimmerian structuring occurred within fully marine conditions (Whitley, 1992). The boundary between Jurassic and Cretaceous is marked by an unconformity which is represented by a fall in relative sea level (Blystad et al., 1995). During Jurassic-Early Cretaceous times, Triassic salt started to move, resulting in the formation of many structural traps on the Mid-Norwegian shelf.

Cretaceous: In Early Cretaceous times the Møre and Vøring Basins subsided rapidly while the Trøndelag Platform was little affected and subsided little. This resulted in the deposition of thick marine shale units with thin carbonate and sand beds over the Halten Terrace. In mid-Cretaceous times extensional tectonics activity gradually decreased and ultimately ceased. During the late Cretaceous, the Møre and Vøring Basins as a whole, together with Halten Terrace and Trøndelag platform began to subside rapidly. This is related to the gradual cooling of the thermal anomaly that was initiated by late Kimmerian rifting pulse.

The thick marine Cretaceous shale units in the area comprise the Cromer Knoll and Shetland Groups (Figure 2-6). The formations representing these groups are deposited as transgressive and high-stand marine shales and mudstones onlapping the Cimmerian unconformity of the relatively raised, rotated and eroded fault blocks (Whitley, 1992). Along these marine sediments occasional turbiditic sandstones are also present.

2.1.3. Cenozoic Development

During earliest Tertiary, sea floor spreading occurred along a plate boundary in the North Atlantic, continuing into the Labrador Sea. The crust between Norway and Greenland, which had been subjected to several extensional phases during the Mesozoic without complete crustal break-up, was attenuated with oceanic crust creation beginning in 57.7 Ma. The oceanic opening was probably accomplished by uplift of the surrounding land areas. Until 36 Ma, Greenland moved in north-westwards direction relative to Eurasia, causing a transpressive regime with Svalbard. At this time the plate geometry changed, and Greenland has since moved westward relative to Eurasia (Bukovics and Ziegler, 1985).

Palaeogene crustal separation: The rate and geographical extent of rifting increased in the Paleocene but was centred on the future break up axis of the Greenland and Fennoscandian cratons. This new rifting pulse was accompanied by Paleocene-Early Eocene Thulean volcanic activity. The crustal separation was achieved in the Norwegian-Greenland Sea

during Early Eocene. After the crustal separation, the subsidence of the Mid-Norwegian shelf area was controlled by lithospheric cooling, contraction and loading by water and sediments.

Another important event at the Halten Terrace and Trøndelag Platform in Cenozoic times is the deposition of 1 km glacio-marine clastics accompanied by rapid subsidence starting in the late Pliocene and going through to Quaternary (Figure 2-5). This rapid burial resulted in deepening and heating of the underlying strata throughout the margin with consequent acceleration of hydrocarbon generation and migration. The formation of diagenetic illite is related to this rapid subsidence (Ehrenberg and Nadeau, 1989).

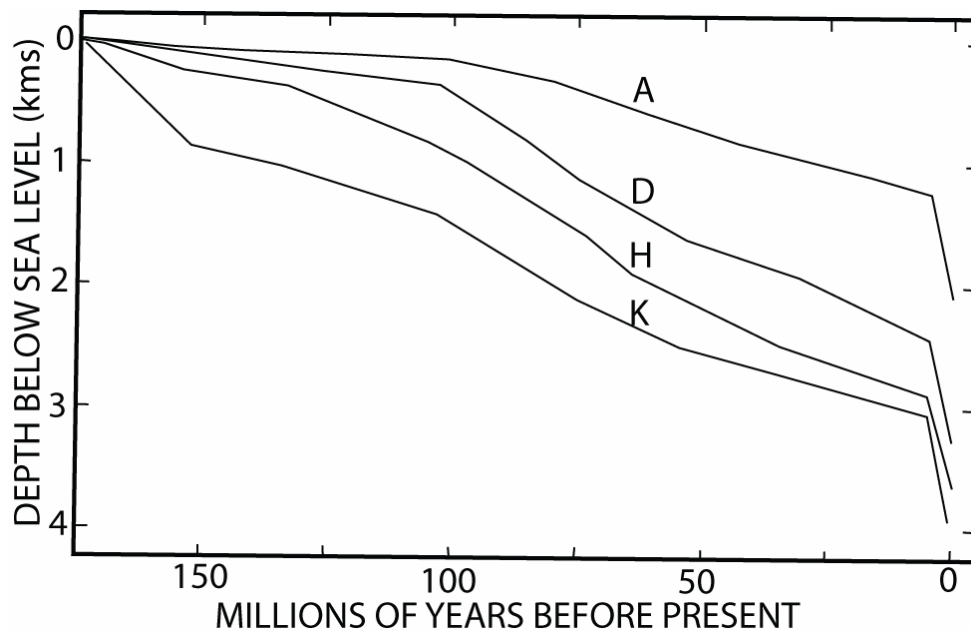


Figure 2-5: Compaction corrected burial histories for the Garn Formation in some of the wells in the present study (redrawn from Ehrenberg, 1990).

Cenozoic sediment infill: The Cenozoic strata in the Mid-Norwegian shelf are 2-3 km thick and were sourced from the Norwegian mainland and inner continental platform to the east. *Paleocene strata* (66.0-59.5 Ma) were deposited as a relatively thin cover on the Mid-Norwegian continental shelf. *Eocene strata* (54-46.5 Ma) are generally thin over the outer continental shelf, but increase in thickness in a landward direction, reaching about 1 km on the present inner shelf. The strata consist of clinoforms that prograded from the east to west and are interpreted as deltaic and related sediments. The distribution of Oligocene strata in the area is somewhat equivocal. Across the middle and outer continental shelf, the Oligocene section is generally missing or extremely thin (Dalland et al., 1988).

The *Miocene section* (18-5.5 Ma) consists of a wedge of strata that onlaps the distal toe of the Eocene clinoforms. The wedge is restricted aerially to the western portion of the present continental shelf, and is 400-500 m thick. The Miocene sequence typically consists of low patterns. These strata are thin in the study area, making them difficult to interpret on seismic. In the northern part of the mid-Norwegian continental margin, where Miocene strata are thickest, the quality of the seismic data does not permit any detailed interpretation of sequence stratigraphic relationships. The downlapping configuration of intra Miocene reflections and the geometry of the base Miocene reflection, however, indicate a marine flooding surface. In the middle and southern part of the study area both seismic (Henriksen and Vorren, 1996) and microfossil data (Poole and Vorren, 1993) indicate that the Miocene strata comprise several sequences.

The top of the Miocene strata is a composite surface (sequence boundary and flooding surface); the strata have extensive erosion, thereby defining an unconformity. The surface is also recognised as a regional downlap surface by the overlying strata, thus defining a major flooding surface. This flooding surface also defines the base of a thick Pliocene-Pleistocene prograding system (Poole and Vorren, 1993). The upper Miocene deposits rest on the present outer continental shelf, whereas the lower Pliocene deltaic deposits rest on the inner shelf. Thus, a significant eastwards shift in the locus of sedimentation was associated with this major transgression and downlap surface; however, recently a well that penetrated these successions (the deltaic complex) showed indications of an early Oligocene age. An alternative interpretation is that the surface may define the top of the deltaic complex, postdating the deltaic deposition. Although there are conflicting ages for these successions, the regional stratigraphic relationships and age dates from other wells suggest the early Pliocene is preferred age for the sequence in deltaic complex (Henriksen and Weimer, 1996).

In another interpretation Neogene succession has been divided into two unconformity bounded successions which are referred to as the lower and upper Neogene successions. These successions have been dated as Miocene –early Pliocene and early Pliocene –Holocene, respectively in age. Development of these unconformity bounded Neogene successions reflects plate-wide, tectonically driven changes in the sedimentary, oceanographic and laterally climatic evolution of the NE Atlantic region (Stoker et al., 2005).

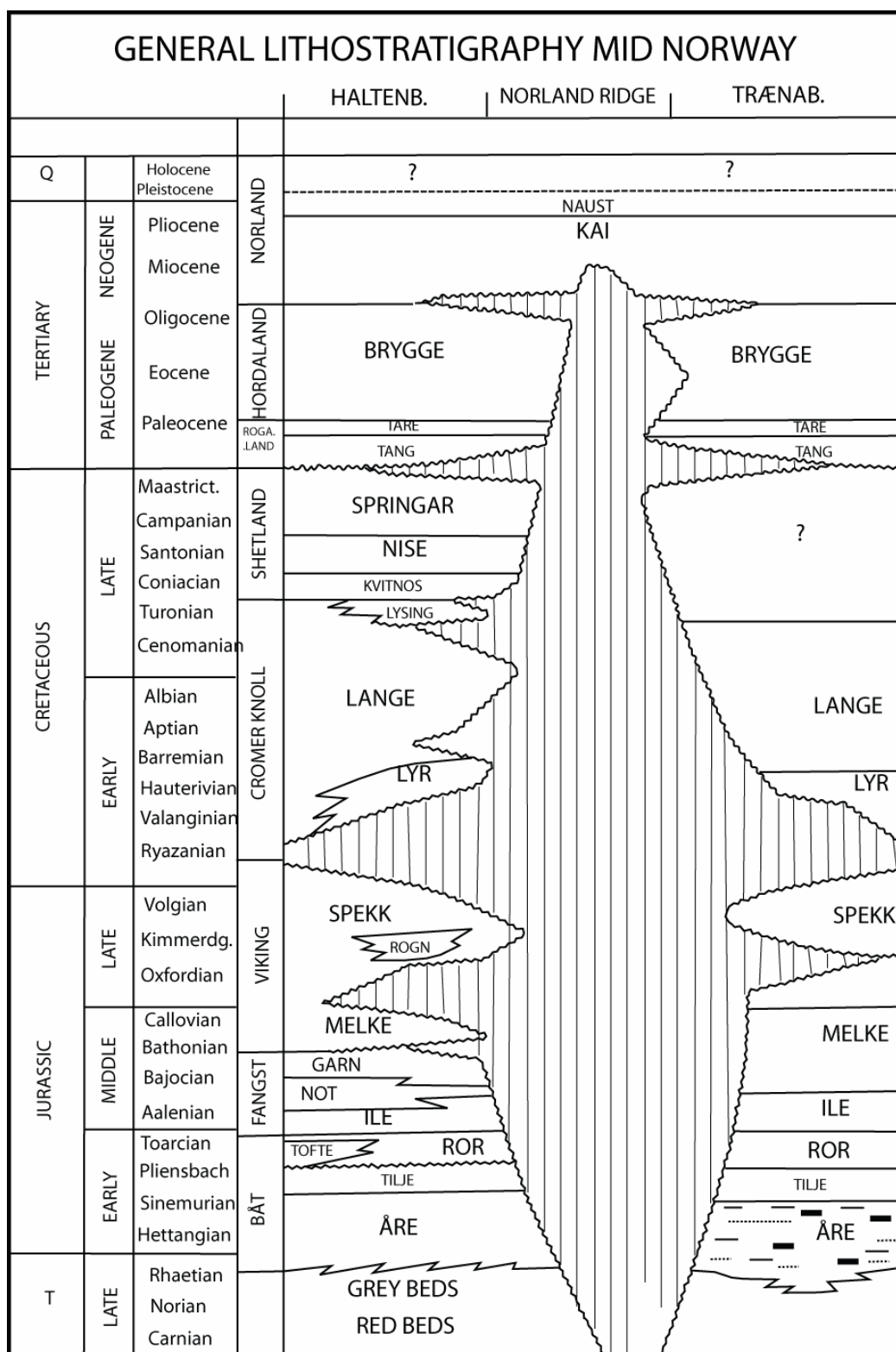


Figure 2-6: Generalized time- and lithostratigraphic section from the Halten Terrace to the Træabanken area (redrawn from Dalland et al., 1988).

The lower Neogene succession mainly consists of deep-water sedimentation that indicates an expansion of contourite sediment drifts above submarine unconformities, within this succession, on both sides of the eastern Greenland–Scotland Ridge from the mid-Miocene

(Stoker et al., 2005). The upper Neogene succession mainly preserves a record of regional change, at about 4 Ma, in the patterns of contourite sedimentation (submarine erosion, new depocentres) coeval with the start of rapid seaward-progradation of the continental margin by up to 100 km. This build-out of the shelf and slope is inferred to record a marked increase in sediment supply in response to uplift and tilting of the continental margin. Associated changes in deep-water circulation have been suggested to be part of an Atlantic-wide reorganisation of ocean bottom currents (Stoker et al., 2005).

Glacial sediments are supposed to form a major component of the prograding shelf margin sediment wedges, but stratigraphic data indicate that the start of progradation pre-dates significant high-latitude glaciation by at least 1 Ma, and expansive Northern Hemisphere glaciation by at least 3 Ma (Stoker et al., 2005).

Stratigraphy: The Cenozoic stratigraphy is formally defined as the Rogaland Group, Hordaland Group and Nordland Group. In the Norwegian Sea area Palaeocene Rogaland Group is mainly composed of clay-stone with minor local siltstone whereas tuffaceous mudstone is common in the upper part. These sediments are about 135 m thick and interpreted to have been deposited in a deep marine environment. In the Haltenbanken area this group is further subdivided into Tang and Tare Formations (Martinsen et al., 1999).

The Eocene to early Miocene Hordaland Group consists of claystone and minor sandstone whereas the sand content increases to the east. The sandstone and claystone succession is about 450 m thick and mainly deposited in marine deepwater. In the Nordland Ridge and Haltenbanken areas this group comprises only of Brygge Formation; however, lateral facies changes and breaks in the succession may form the basis for further subdivision (Dalland et al., 1988).

The youngest, and most important for the present study point of view, is the early Miocene to Recent Nordland Group. It was deposited in marine environment in a rapidly subsiding basin characterised by major westerly prograding clastic wedges. The upper part is supposed to be of glacial to glacio-marine origin (Dalland et al., 1988). This group is further subdivided into Kai and Naust Formations that are described below; if not otherwise stated the description is taken from Dalland et al. (1988).

Kai Formation consists of alternating claystone, siltstone and sandstone with limestone stringers whereas glauconite, pyrite and shell fragments are common. Apart from the Nordland ridge, this unit is present throughout the study area. These early Miocene to late Pliocene sediments are interpreted to be deposited in marine environments with varying water depths.

The deltaic *Molo Formation* has been biostratigraphically dated to the Oligocene (Eidvin et al., 2000), but re-dating suggest an early Pliocene age (Eidvin and Rundberg, 2001). Molo formation have been seismically mapped by (Rokoengen et al., 1995) as unit IX but no detailed description of the lithology have been found (Figure 2-7).

The late Miocene to early Pliocene *Utsira Formation* (Figure 2-7) consists, at its lower part, thick marine, mounded sand bodies, interpreted as overall stacked lowstand fan deposits, while the upper part of the formation consists of more clayey-silty intervals, indicating increased relative sea level. The Utsira Formation have been subdivided into four log-units and mapped, and two main depocentres are outlined (Gegersen et al., 1997). The sandy Utsira Formation could have been deposited in a geostrophic-induced, contourite drift complex (Galloway et al., 1993), but has also been interpreted as a tidal sand ridge complex (Rundberg, 1989). Rapid deposition of the marine sandy deposits may have triggered extensive gravity deformation of underlying muddy, gas-charged Oligocene and Lower Miocene deposits (Galloway et al., 1993).

Naust Formation mainly consists of interbedded claystone, siltstone and sand, occasionally with very coarse clastics in the upper part. This package of sediments is laterally continuous across the Mid-Norwegian Shelf and has been deposited in a marine environment with a transition to glaciomarine environment occurring in upper part. It has been designated Late Pliocene age (Blystad et al., 1995).

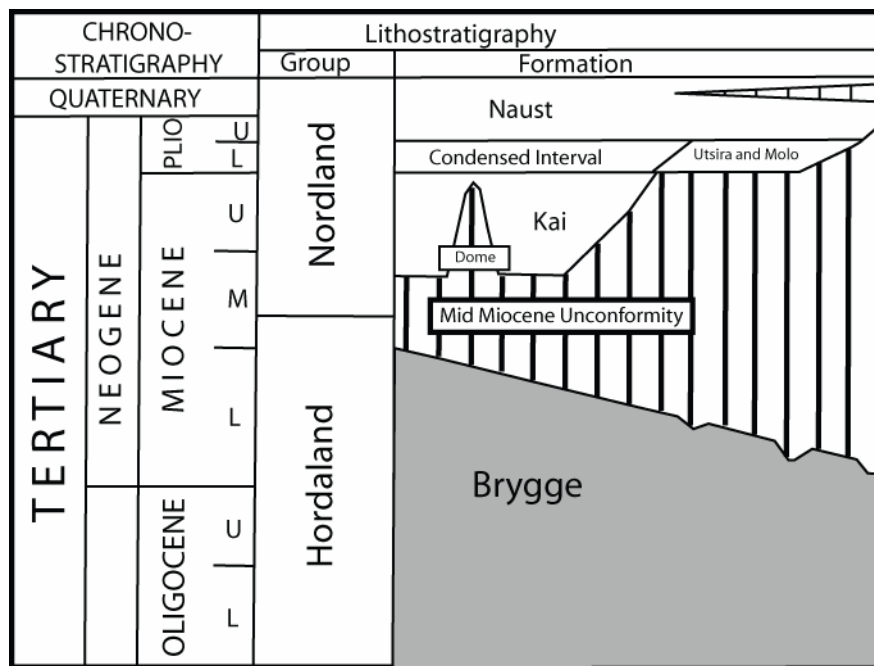


Figure 2-7: Simplified stratigraphy of the Late Cenozoic showing new relationship between the Utsira/Molo formation (redrawn from Løseth and Henriksen, 2005).

3. Data and Methods

Geophysical and geological data and methods used in this study are presented in this chapter. The data include multi-channel seismic reflection and well data which are all described in initial part of this chapter. The method of sequence stratigraphy is presented briefly with special emphasis on seismic sequence analysis in last part of this chapter.

3.1. Data

The Data are presented in maps by the Generic Mapping Tools (Wessel and Smith, 1995). The UTM (Universal Transverse Mercator) zone 32 with 9°E as central meridian was used.

3.1.1. Seismic data

The multichannel seismic reflection surveys (Figure 3-1) are the basis for the seismic sequence stratigraphic interpretation and seismic facies analysis. Approximately 30,000 km of multichannel 2D seismic reflection data have been interpreted on a CharismaTM (Geoframe) workstation. Multichannel seismic data include mostly regional seismic lines which cover up to 300 km in dip direction from the Trøndelag Platform to the Vøring Marginal High and up to 400 km strike direction from northern North Sea to Nordland Ridge area. Data coverage is best in southern part of the study area including northern North Sea and southern Møre Basin and the Trøndelag Platform area in northern part of study area. However the data coverage in central part of the study area (Storegga Slide area and western parts of Trøndelag Platform, areas south of Vøring Basin) is less dense. In this study main emphasis has been down to 3 s two way travel time (TWT) on most of the seismic lines.

It was not possible to do detailed sequence stratigraphic interpretation in Storegga Slide area partly because of disturbed and reworked geology due to sliding and partly because of poor data coverage.

Some of the important seismic surfaces have not been possible to trace through the Storegga area and in some cases surfaces have been linked across the area by merging them with older surfaces assuming zero thickness. The data coverage in western parts of Helland-Hansen Arch is very low and therefore interpretation beyond the ridge is not very good.

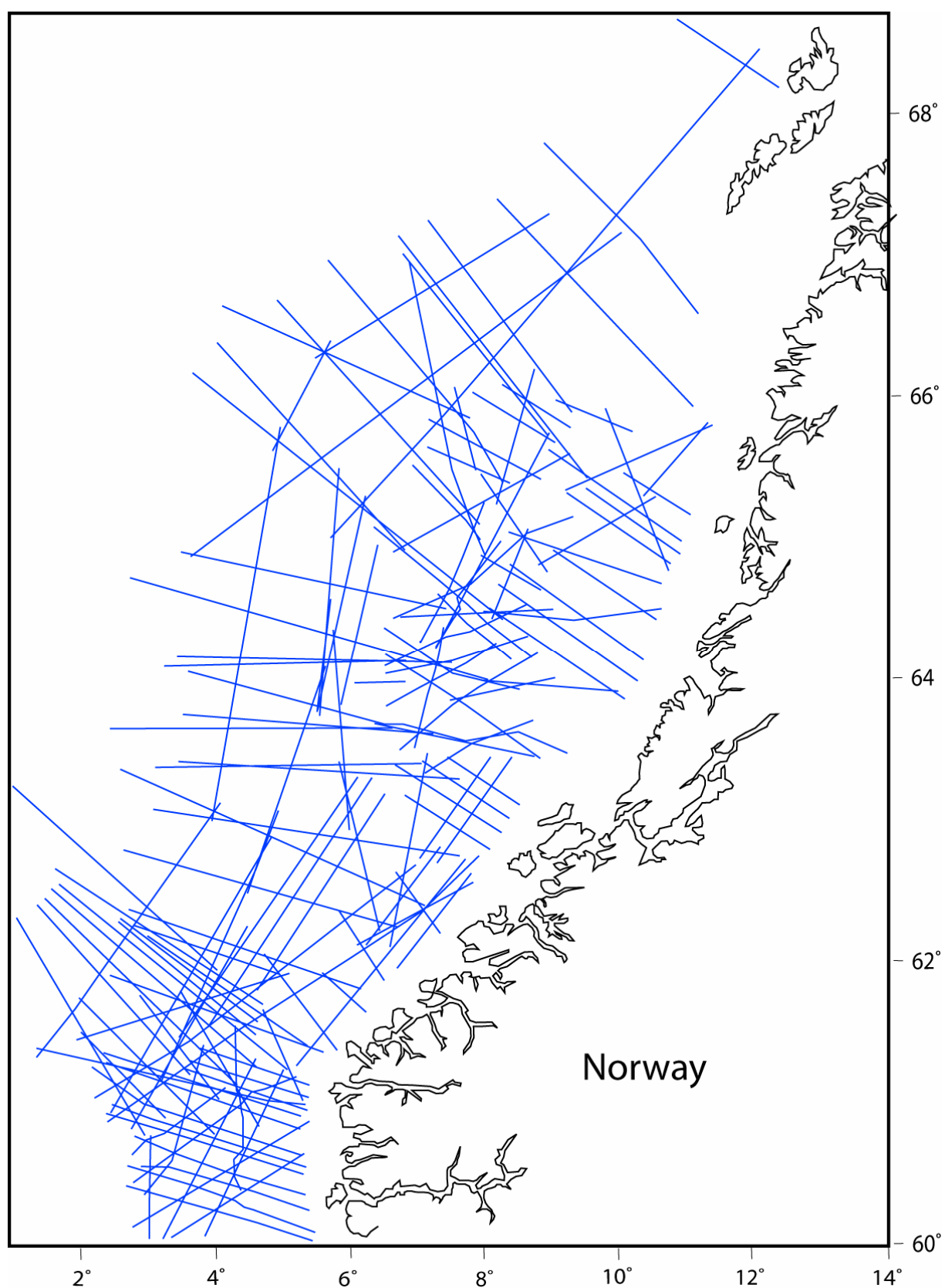


Figure 3-1: Map showing the location of the seismic lines used in this study.

3.2. Sequence Stratigraphy

Modern sequence stratigraphy has developed from the integration of high resolution seismic data, and stratigraphic and sedimentological principles. The eustasy-driven Exxon model of sequence stratigraphy from late 1970's, based on interpretation of multi-channel seismic data, is considered to be very important for all further development of sequence stratigraphy model. The AAPG Memoir 26 (Payton, 1977) contains a collection of papers presenting these principles and models.

The Exxon model on sequence stratigraphy and global sea-level changes has been criticized by several authors (Miall, 1986; Pitman, 1978; Summerhayes, 1986). A revision and further development of the passive margin Exxon sequence stratigraphic model was published by Vail (1987) and was the prominent theme in the SEPM Special Publication No. 42 (Wilgus et al., 1988). The definition of sequence, sequence boundary, parasequence and marine-flooding surface, among others, was redefined in this publication.

The development of sequence stratigraphy has led to several interrelated sequence stratigraphical models or methods (Figure 3-2). Individual models are distinguished by their specific definitions of the sequence boundary and in part also by the inferred genesis of sequence. The models include the use and combination of various types of data, including seismic, well and outcrop data, and take into account biostratigraphy, ichonology, petrography and geochemistry. Nevertheless, the depositional (Exxon model), the genetic stratigraphic (Galloway model) and the T-R (Embry model) models are generally considered as major models in modern sequence stratigraphy. Hence, Figure 3-3, Table 3-1 summarised the main aspect of these models.

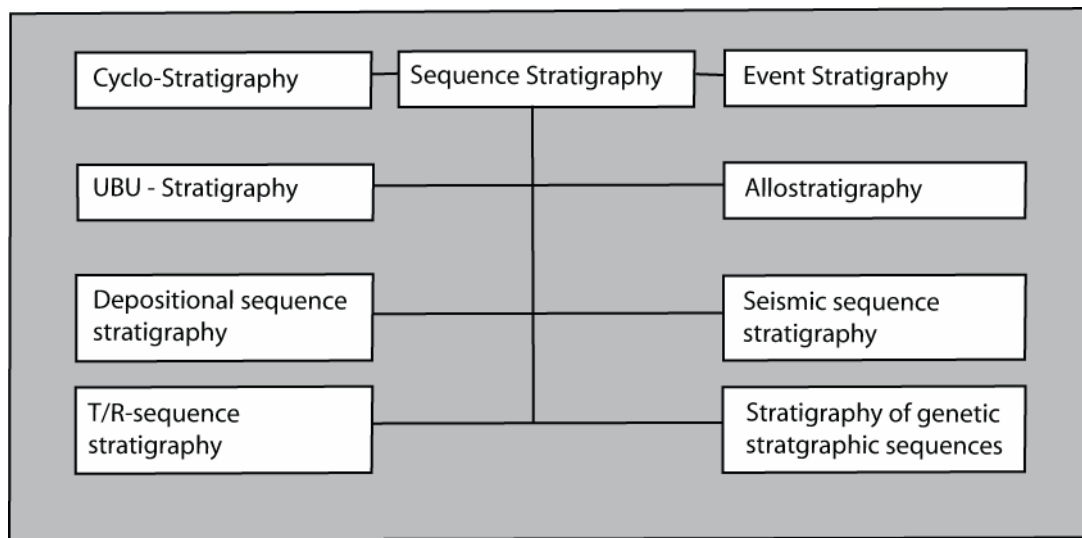


Figure 3-2: The family tree of sequence stratigraphic systems, cyclo- and event stratigraphy (redrawn from Nystuen, 1998) (UBU-unconformity-bounded units, T/R- Transgressive / Regressive system tract).

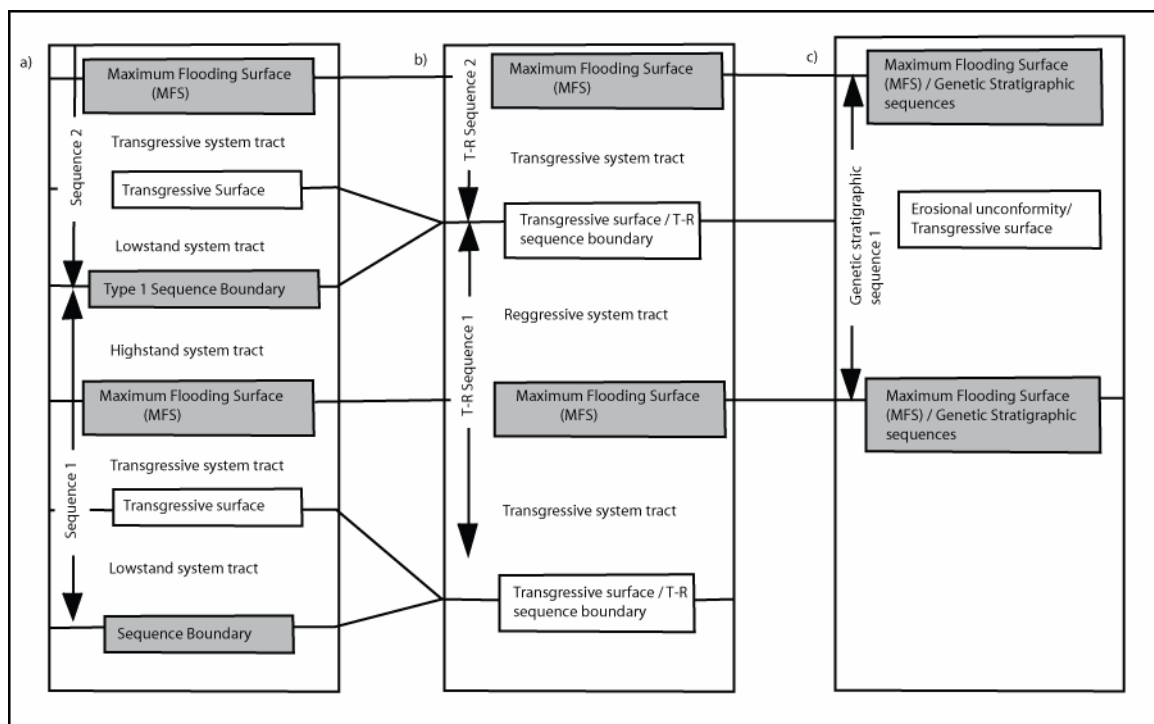


Figure 3-3: Comparison of how the sequence stratigraphic unit is defined in the a) depositional sequence (Exxon model) b) T-R sequence (Embry model) and the c) Genetic stratigraphic sequence (Galloway model) (redrawn from Pedersen, 1998)

Table 3-1: Models in modern sequence stratigraphy with main references (modified from Pedersen, 1998).

Type	Characteristic	References
Cyclo – Stratigraphy	Cycles defined as time unit of regular duration or periodicity	Schwarzacher (1993)
Event Stratigraphy	Stratigraphic events formed by some episodic process of geologically short duration at irregular or non periodic time intervals	Dott (1988), Einsele et al., 1991
UBU – Stratigraphy	Unconformity bounded units	Chang (1975), Hesberg (1976), Salvador (1994)
Allostratigraphy	Nongenetic units bounded by laterally traceable mappable disconformities, defined independently of inferred geologic history and time spans	North American Commission on Stratigraphic Nomenclature (1983)
Depositional sequences stratigraphic model (Exxon model)	Sequence stratigraphic unit bounded by sub-areal unconformities and their correlative marine conformities. Sequence development eustasy-driven, or modified to be driven by changes in relative sea level	Vail et al., (1977), Van Wagnor et al., (1988)
Seismic sequence stratigraphy	Study of stratigraphy and depositional facies as interpreted from seismic data	Mitchum (1977)
Genetic sequences stratigraphy (Galloway modell)	Sequence stratigraphic unit deposited during one depositional episode and bounded by maximum flooding surfaces and their landward correlative surfaces.	Galloway (1989)
Transgressive- Regressive sequence stratigraphy (Embry model)	Sequence stratigraphic unit bounded by regionally extended subaerial unconformities and their correlative transgressive surfaces	Embry (1993,1995)

3.2.1. Sequence stratigraphic models

The fundamental unit is the Sequence, which is divided into system tracts. *Depositional system tracts* are contemporaneous depositional systems defined on the basis of stratal geometry at the bounding surfaces and parasequence stacking pattern, which indicate the position in the sequence (Shanley and McCabe, 1994). The systems tracts represent the depositional system through which sediment is transported from continental to marine realm. The *geometric system tracts* are identified by seismic reflectors and are geometrically defined. Different genetic system tracts refer to different positions of relative sea-level as the system tracts were formed (Nystuen, 1998).

The *depositional sequence*, or just the *sequence*, of Exxon, which is applied in the present study, is defined as “a relatively conformable succession of genetically related strata bounded by unconformities and correlative conformities” (Mitchum, 1977; Van Wagoner et al., 1988). The sequence boundary (SB) is a subaerially formed erosional unconformity and its correlative marine conformity (Van Wagoner et al., 1988). The Exxon sequence is subdivided into the highstand, lowstand and transgressive system tracts (Posamentier et al., 1988). The T-R sequence model (Embry, 1995) consists of the transgressive and regressive systems tract, with the transgressive surface (TS) as sequence boundary. The *genetic stratigraphic sequence* (Galloway, 1989), having the maximum flooding surface (MFS) as sequence boundary, is divided into the regressive and transgressive systems tracts. In addition to the three systems tracts of the Exxon model, the forced regression systems tract (e.g. Hunt and Tucker, 1995) includes sediments deposited and preserved during the falling stage of the sea level.

3.2.2. Seismic Stratigraphy

The basis of this method is to use an integrated geological/geophysical database to define the sedimentary record in terms of sequences. The seismic sequences (SS) are separated by regionally extended unconformity surfaces and form the fundamental stratigraphic building blocks of basin analysis. The method of seismic stratigraphy consists usually of several steps. (Vail, 1987) introduced seven steps for seismic stratigraphic interpretation. However, only some of these could be used in this study because of the limited well data.

Seismic sequence analysis

The objective of seismic sequence analysis is to interpret depositional sequences on seismic sections by identifying discontinuities on the basis of reflection terminations. The techniques

and ideas for seismic sequence analysis were published by the Exxon group in the late 1970's (Vail et al., 1977). The techniques subdivide a seismic section into package of concordant reflections separated by sequence boundaries. The identification of a sequence boundary is based on the reflection termination patterns as onlap, downlap, toplap and erosional truncation (Figure 3-4).

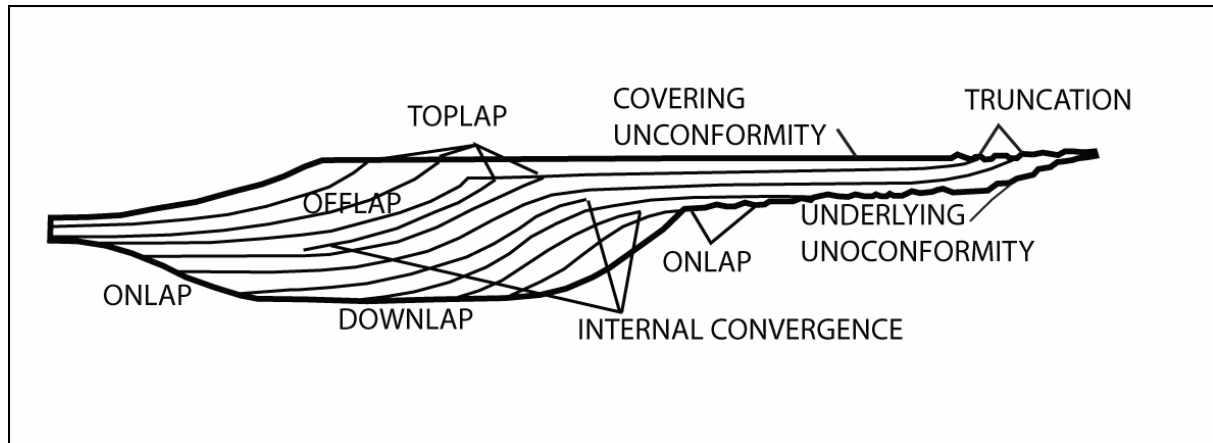


Figure 3-4: Seismic stratigraphic reflection terminations within idealised seismic sequence (redrawn from Mitchum et al., 1977).

Seismic facies analysis

Mitchum et al., (1977) and Sangree and Widmier, (1977) described seismic facies analysis as the interpretation of the environment and lithologies from seismic reflection data. It involves the delineation and interpretation of reflection parameters, as well as the external and three dimensional associations of groups of reflection patterns (Table 3-2); produced by reflection geometry, continuity, amplitude, frequency and interval velocity. By integrating these data the facies units can be interpreted with environmental setting, depositional setting, depositional processes, and estimates of lithology.

There is no single characteristic seismic reflection property that provides a unique guide to the recognition of individual facies. For example continuous flat-lying reflections may reflect deep-marine shale, coastal-plain topset, and alluvial plain or lacustrine facies. However, a seismic facies map may be used to construct one or more geological models, which idealistically should be calibrated by well control. Without well control, a seismic facies map generally remains open to several geological interpretations. Each facies unit should be studied in relation to the neighbouring units, and paleo-topography should therefore be considered to ensure that the most probable interpretation of seismic data is made.

Table 3-2: Terminology proposed by Mitchum et al. (1977) to describe reflection terminations, reflection configuration, and geometry of seismic facies.

Reflection termination (at sequence boundaries)	Reflection configurations (within sequences)	External forms (of sequences and seismic facies units)
Lapout	Principal stratal configurations	Sheet
Baselap	Parallel	Sheet drape
Onlap	Subparallel	Wedge
Downlap ¹⁾	Divergent	Bank
Toplap	Prograding clinoforms	Lens
Truncation	Sigmoid	Mound
Erosional	Oblique	Fill
Structural	Complex sigmoid-oblique	
Concordance (no termination)	Shingled	
	Hummocky clinoform	
	Chaotic	
	Reflection-free	
	Modifying terms	
	Even Hummocky	
	Wavy Lenticular	
	Regular Disrupted	
	Irregular Contoured	
	Uniform Variable	

Table 3-3: Seismic reflection parameters used in seismic stratigraphy, and their geological significance. After Mitchum et al. (1977).

Seismic facies parameters	Geologic interpretation
Reflection configuration	Bedding patterns Depositional processes Erosional processes Fluid contacts
Reflection continuity	Bedding continuity Depositional processes
Reflection amplitude	Velocity-density contrast Bed spacing Fluid content
Reflection frequency	Bed thickness Fluid content
Interval velocity	Estimation of lithology Estimation of porosity Fluid content
External form & areal association of seismic facies units	Gross depositional environment Sediment source Geologic setting

3.3. Methods

3.3.1. Seismic Stratigraphic Interpretation

Seismic interpretation work presented here is done using CharismaTM (Goframe) tool in mid-Norway continental margin (see Figure 3-1 for location of seismic lines). The interpretation focuses on examples of unconformities and sediment wedges, regarded as two of the major

ingredients of sequence stratigraphic interpretation with one being erosional and the other depositional. Interpretational procedure follows the following main steps (Emery et al., 1996):

Identification of unconformities

Unconformities are surfaces representing a break in deposition and are usually accompanied by erosion. On seismic sections they have been recognized as surfaces onto which reflectors converge and or terminates.

Marking reflection termination with arrows

After identification of reflection terminations these have been categorized into onlap, toplap, and downlap terminations which then have been marked by recommended arrow symbols.

Drawing the unconformities

Once reflector terminations are marked with arrows, these surfaces are then drawn between the onlapping and downlapping reflections above; and the truncating and toplapping reflections below.

Extending the unconformities over the entire section

Unconformities identified and drawn from reflector terminations are then extended over the entire seismic sections. It is very common that these boundaries become conformable; their positions are traced across the section by visually correlating the reflections.

Continue identification of unconformities on remaining seismic sections

The boundary interpreted as unconformity on one section is then extended on the other seismic lines near the first one. Parallel lines were examined to see if it is possible to find similar truncations and tracing the same surface. When possible, then the surfaces are traced on as many lines nearby as possible and then all the lines are connected with a line crossing these lines. Sometimes it is difficult to find exactly same surfaces on adjacent lines; in that case a crossing line is selected and tie points from earlier interpreted lines are traced by correlating the reflections.

Tying the interpretation among all lines

More and more tie points are obtained by tracing similar surfaces on different lines parallel and crossing to each other. These points are connected further into the area under consideration to trace the surface in as large area as possible. Some surfaces are of regional extension but some are only local.

Identification of the type of unconformities, conformities on remaining seismic sections

Following similar procedure all the other possible unconformities are identified and extended in the study area. Once interpretation of these surfaces are done, these surfaces are then

classified based on the configuration of their bounding truncations. An unconformity has been classified as sequence boundary if it is characterized by regional onlap above and truncation below. A *downlap surface (DS)* is a seismic surface that is characterized by a series of clinoform surfaces downlapping onto it over an area large enough to be mapped from several dip- and cross lines. Downlap surfaces can be traceable all over the investigated area as *regional downlap surfaces (RDS)*, or *local downlap surfaces (LDS)* of variable lateral extent. Downlap surfaces generally imply rise in accommodation space, due to rise of relative sea level (Emery et al., 1996).

3.3.2. Seismic Facies Analysis; Recognition, Mapping and Interpretation

After seismic sequences are defined, environment and lithofacies within the sequences are interpreted from seismic and geological data. Seismic facies analysis is the description and geologic interpretation of seismic reflection parameters. These parameters, includes internal reflection configuration, external forms, three dimensional associations of these facies, amplitude, continuity, frequency, and interval velocity.

In this study seismic facies units have been identified, their internal reflection configuration, external forms and three dimensional associations of these facies units have been recognised and interpreted using simplified approach explained by (Vail et al., 1977).

There are several alternate approaches to seismic facies analysis, depending upon the parameters analyzed and the purpose of analysis. Although our discussion is limited to visual inspection of these parameters, especially seismic reflection configuration, more quantitative approaches are available through the use of modern computer programs (Mitchum et al., 1977).

3.3.3. Construction of Chronostratigraphic Charts

A chronostratigraphic chart of the mapped sequences has been constructed from a representative seismic section by following the procedure given by Emery and Myers (1996). The reflections considered to be time lines from the seismic section have been plotted in order of age, with an equal time increment given to each reflection. This has been done due to the lack of absolute ages of the time lines, except for a few. When data on absolute ages will be available from any parts of the studied succession, the chronostratigraphic chart can be rescaled to absolute time. However, as absolute ages are available for a few key boundaries only, the time scale of the chart between these boundaries still has to be given as relative ages. The young Cenozoic package of sediments has not been properly studied and dated in wells

which ties to these seismic sections. So, we therefore have not added any well data into chronostratigraphic chart.

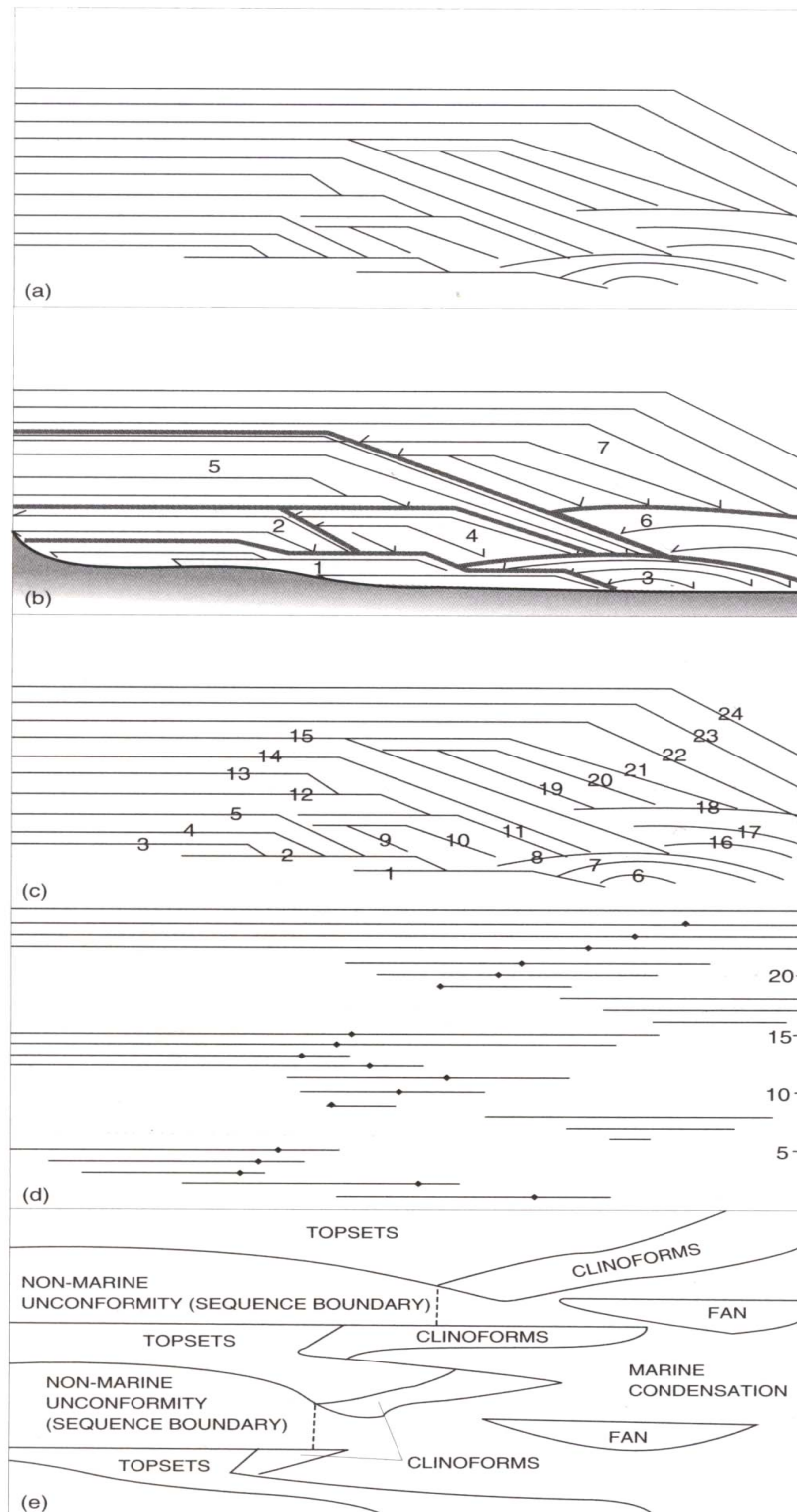


Figure 3-5: The process of construction of a chronostratigraphic chart from seismic data; (a) a sketch seismic line; (b) a seismic stratigraphic breakdown of the line; (c) numbering of the reflections; (d) transfer of the reflection to a time axis, in numeric order; (e) a chronostratigraphic interpretation of the seismic data (Emery et al., 1996).

4. Results / Seismic Interpretation

The seismic sequence interpretation is presented in this chapter and illustrated by examples of interpreted seismic sections, type sections for each seismic sequence and time thickness contour maps and selected digitized seismic sections. Initial part of this chapter presents the results of seismic sequence analysis together with the thickness and distribution of individual seismic sequences along the mid Norwegian continental margin. Seismic facies interpretation is presented in the later parts of this chapter. The seismic interpretation has mainly been done by using interactive seismic interpretation tool Charisma. A combination between interpretation on colour seismic sections, printed from Charisma, and workstation interpretation is used for the seismic facies interpretation.

Table 4-1: The seismic division, Seismic stratigraphic boundaries and Seismic sequences (SS)

Seismic stratigraphic surfaces	Seismic sequences
URU	SS 7
UCS 4	SS 6
UCS3	SS 5
UCS2	SS 4
UCS1	SS 3
RDS	SS 2
LDS	SS 1

The Plio-Pleistocene package along the mid Norwegian continental margin has been divided into seven seismic sequences (Table 4-1) on the basis of their geometry and nature of their bounding surfaces. Each of these Plio-Pleistocene seismic sequences has been named as seismic sequence from SS 1 to SS 7. Bounding surfaces are named *local downlap surface* (LDS), *regional downlap surface* (RDS), *unconformity clinoform surfaces* 1-4 (UCS 1-4) and *upper regional unconformity* (URU) (Table 4-1).

4.1. Type sections

A type section is a seismic section or line on which a particular surface was defined as seismic sequence boundary which was then extended in rest of the study area. Four type sections have

been chosen to present the seismic sequence interpretation. The location of these type sections AA', BB', CC', and DD' are shown in (Figure 4-1). The prominent high present on seismic lines in northern part is Helland-Hansen Arch. The seismic sequence boundary LDS (local downlap surface) is the oldest surface and separates the Plio-Pleistocene prograding wedge system from older sediments in the Møre Basin area, while seismic surfaces RDS (regional downlap surface) marks the base of Plio-Pleistocene package in the rest of the study area.

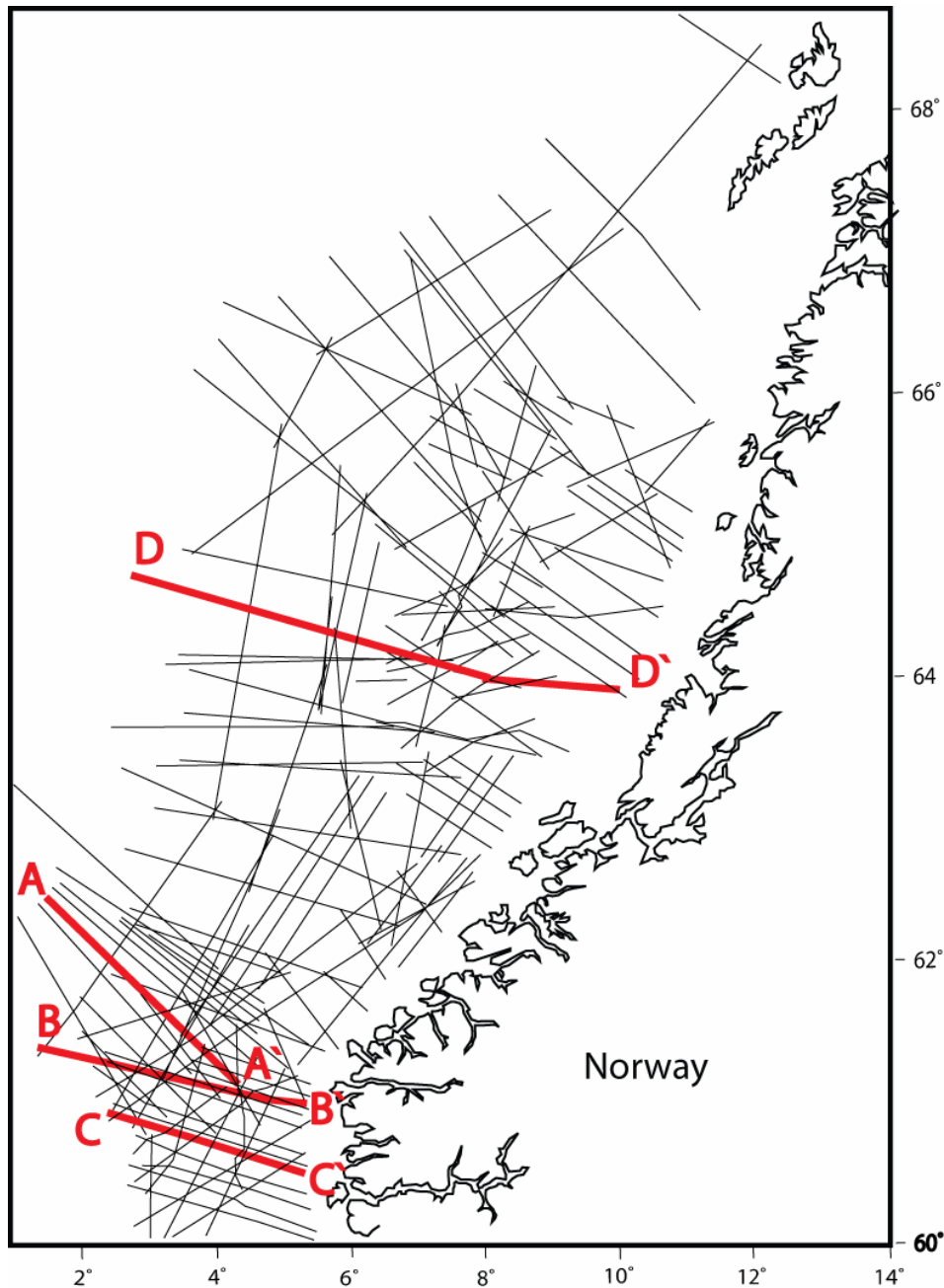


Figure 4-1: Map showing the location of the selected seismic lines described as type sections in the text

Type Section AA`

A line drawing with interpreted seismic sequences of type section AA` is presented in Figure 4-2. The type section AA` consists of the seismic interpretation of line MSS99-112A, but since we are dealing with the Plio-Pleistocene succession so only the upper 3 seconds twt have been used. The section extends approximately 180 km from south-eastern to north-western parts of the Møre Basin (Figure 4-1). This seismic line is type section for the seismic surface LDS (local downlap surface) which bounds the sequence 1 (S1) on its base. The seismic surface LDS is very prominent and easy to identify here and seismic sequence S1 is having its maximum thickness preserved here on this line.

Type Section BB`

A line drawing with interpreted seismic sequences of type section BB` is presented in Figure 4-3. The type section BB` consists of the seismic interpretation of line GMNR-94-101A. This seismic section extends laterally up to 200 km from the southernmost margin of the Møre Basin to out in the basin almost normal to coast line (Figure 4-1). GMNR-94-101A seismic line is type section for most of the seismic surfaces except UCS 2 (unconformity clinoform surface) interpreted in this study. Almost all of these surfaces are very well developed here on this section and therefore it is relatively easy to distinguish different seismic sequences on it in southern parts of the study area.

Type Section CC`

A line drawing with interpreted seismic sequences of type section CC` is presented in Figure 4-4. The type section CC` consists of the seismic interpretation of line NVGTI-92-106A. This seismic section extends laterally about 165 km south of Møre Basin parallel to section BB`. This seismic line is a type section of seismic surface UCS 2 (unconformity clinoform surface 2) which below, towards the east, is characterized by toplap truncation and is conformable with overlying reflectors on the upper, western side. This surface marks the top of seismic sequence three (S3) which has its maximum thickness preserved in this area.

Type Section DD`

A line drawing with interpreted seismic sequences of type section DD` is presented in Figure 4-5. The type section DD` consists of the seismic interpretation of a composite line GMNR-94-310. This seismic line extends laterally up till 400 km from eastern parts of Trøndelag platform to well beyond Helland-Hansen Arch on the west. This line is type section for most of the interpreted seismic surfaces and sequences in the northern parts of the study area. All

the seismic surfaces and sequences are very well presented here on this line with their typical thicknesses present and can be easily differentiated. Offlap lap break is preserved for some of the seismic surfaces as here on this section.

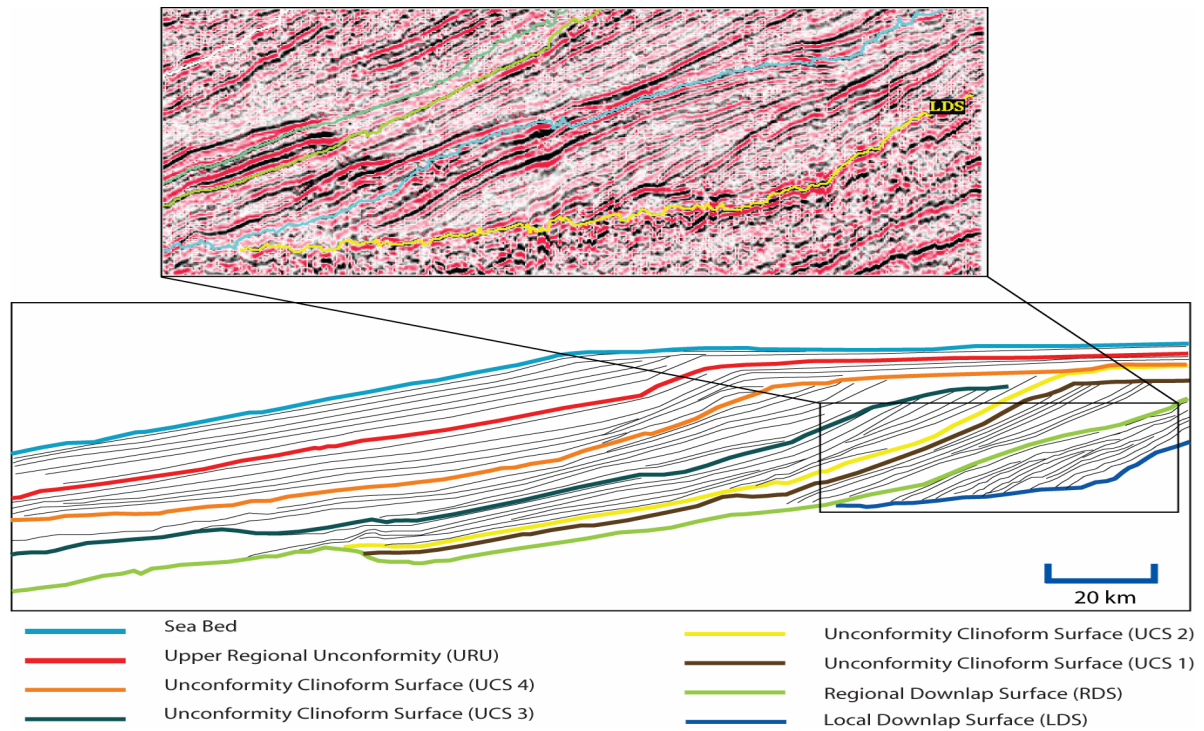


Figure 4-2: Line drawing of the seismic line MSS-99-112 A, the type section AA' for Local Downlap Surface (LDS). Seismic line is shown also shown in the zoom rectangle.

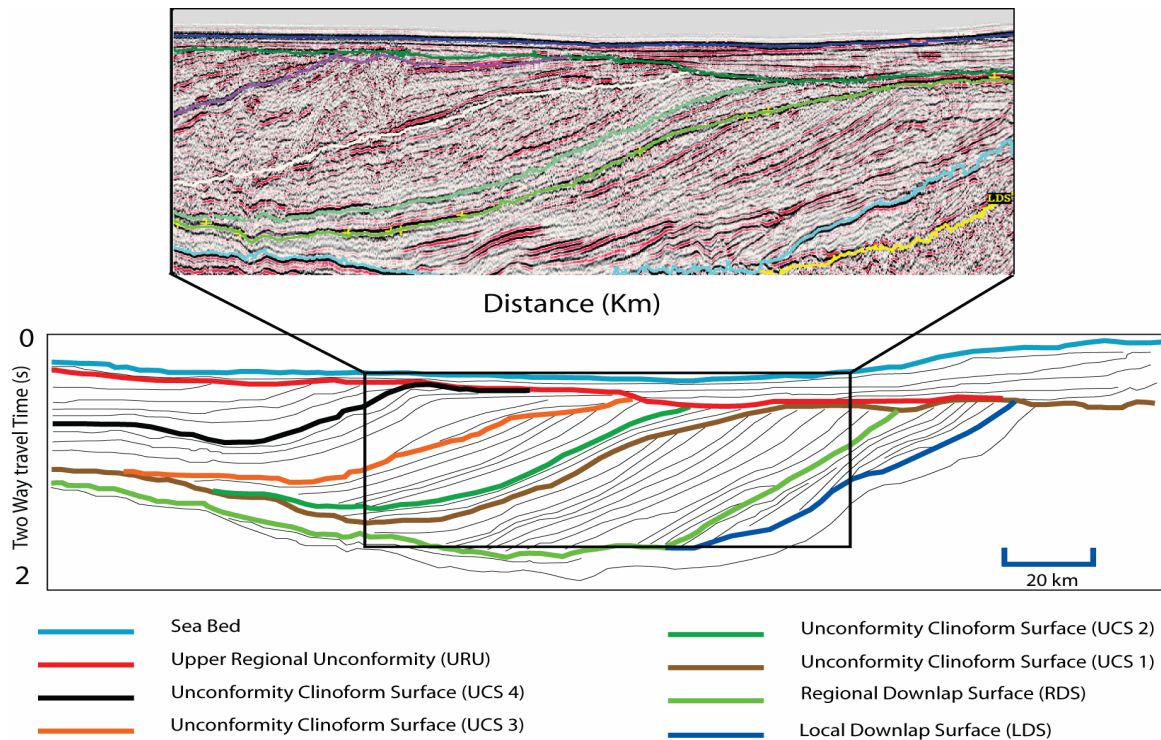


Figure 4-3: Line drawing of the seismic line GMNR-94-101, the type section BB' for most of the seismic surfaces except UCS 2. Seismic line is shown also shown in the zoom rectangle above the line drawing.

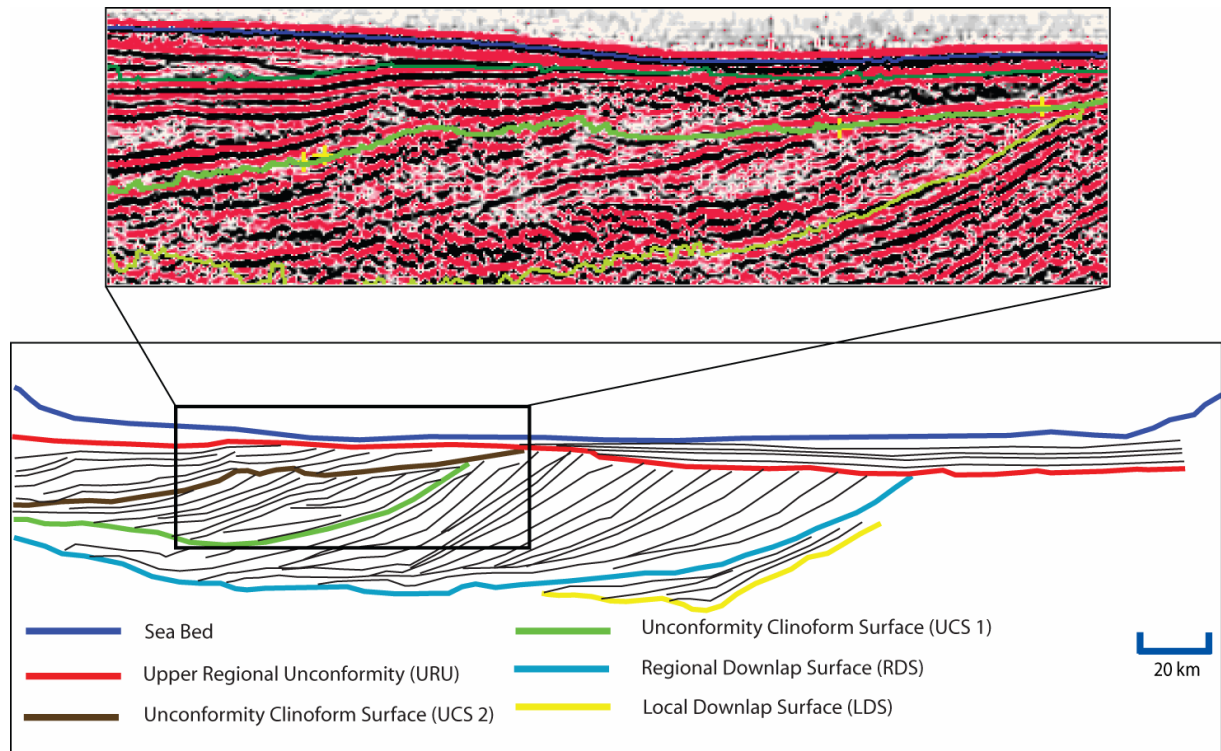


Figure 4-4: Line drawing of the seismic line MNVGTI-92-106 A, the type section CC' for Unconformity Clinoform Surface UCS 2. Seismic line is shown also shown in the zoom rectangle.

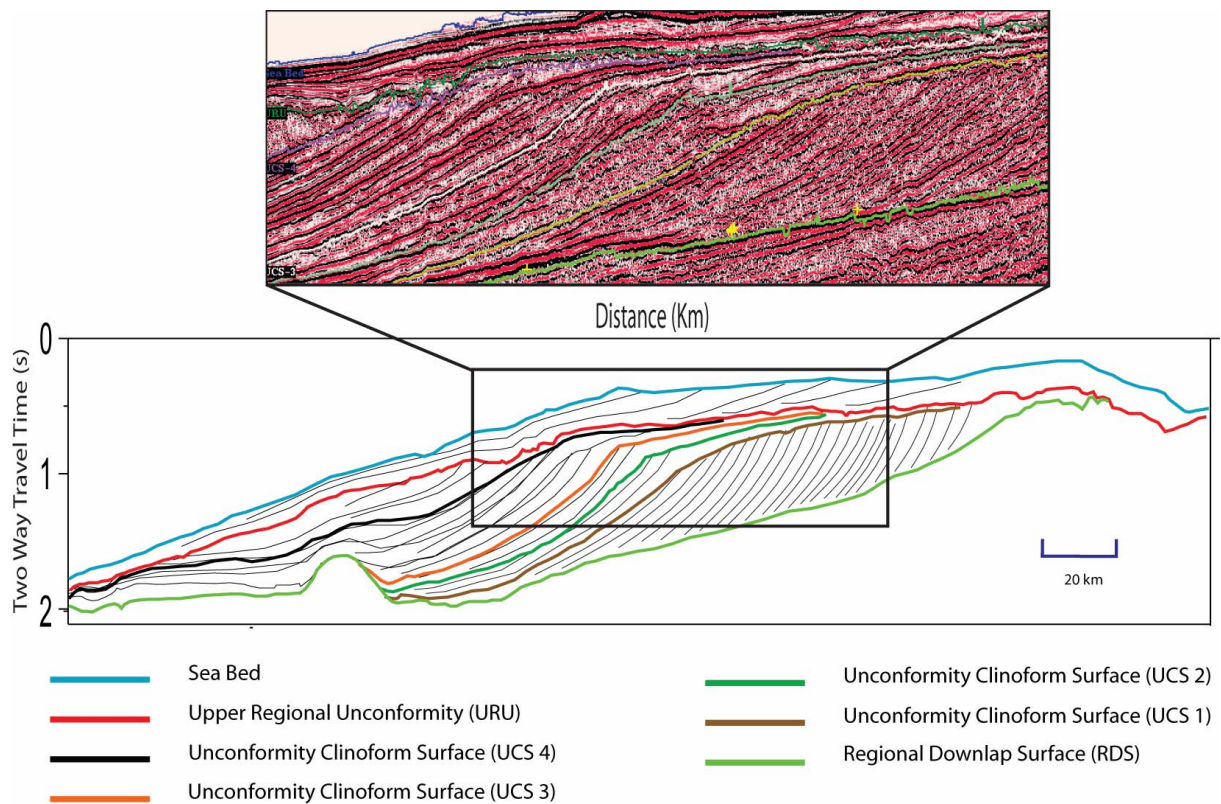


Figure 4-5: Line drawing of the seismic line GMNR-94-310, the type section DD' for almost all the seismic surfaces mapped in northern part of the study area. Seismic line is shown also shown in the zoom rectangle.

4.2. Seismic Sequence Analysis

North of Frøyabanken, below the present day shelf, the base of the Naust Formation is commonly seen as a downlap surface, and it appears to present an angular unconformity along mid Norwegian Continental Margin in most parts of the study area where it has been mapped (Rise et al., 2005), seismic surface RDS in Figure 4-5 and Figure 4-6A for total thickness. The Naust Formation have been subdivided into six seismic sequences (S2, S3, S4, S5, S6, and S7), each comprising several units (Figure 4-5). At outermost shelf and beyond the shelf edge, the layers above and below the base of the Naust Formation are generally conformable. A seismic sequence stratigraphic approach was applied in the study area in order to relate the geological development of the Plio-Pleistocene prograding wedge system to depositional cycles. The sediment succession are considered to consist of several incoherent seismic units (till, glacial debris, slide deposits) interbedded with stratified units deposited in periods between extensive glaciations (Rise et al., 2005).

The following section outlines a description for each interpreted seismic sequence (Table 4-1). The seismic nature of the sequence boundary defining each seismic sequence is also described in this chapter. Each seismic sequence is defined by the lower sequence boundary.

4.2.1. Seismic sequence 1 (SS 1)

The seismic sequence 1 (SS 1) is the lowermost and oldest unit which is bounded by the local downlap surface (LDS) at its base and by the regional downlap surface (RDS) at its top. The lower boundary of this unit is a good seismic surface with internal reflector of SS1 clearly downlapping on it. The LDS thus separates the lower more aggradational kind of package from the upper prograding unit. The upper boundary, RDS, is a good seismic surface in large parts of the study area, but on top of seismic sequence 1 its position is not very clear.

The seismic sequence 1 has its maximum thickness in the Møre Basin. The unit is quite thick in the Møre South area but decreases in thickness towards the north and in the Møre 1 area it is very thin. Towards the Trøndelag Platform the LDS and RDS merge, hence the SS 1 appears to pinch out here (Figure 4-5). In some areas it was very difficult to map the lower bounding surface (LDS) because the prograding units seem to be changing into more muddy units with chaotic seismic character. The progradation of the clastic wedges actually took place above and into hemipelagic to pelagic sediments; the clinoform reflectors of the prograding units thus display an inter-fingering geometry with the parallel or chaotic

reflectors of the hemipelagic sediments, and this give rise to seismic reflectors that are difficult to trace laterally. The boundary in this situation was traced at a margin of good and chaotic seismic reflections (Figure 4-2).

The sequence comprises numerous medium to high angle, wedge shaped prograding depositional units. The geometry of the prograding units suggests that the shelf was relatively narrower, and accommodation space was enough to let this steep angle progradation build out (Figure 4-6 B).

4.2.2. Seismic sequence 2 (SS 2)

The seismic sequence SS 2 is bounded at its base by regional downlap surface (RDS) characterized by regional scale downlapping of clinoforms on it. This is a very distinct seismic surface and interpretable over larger areas of the offshore mid-Norway. The upper boundary of the seismic sequence 2 (SS 2) has usually been observed as a good seismic marker, but it varies locally in character. The upper part of the sequence is commonly bounded by toplap truncation on the middle and eastern parts of shelf but is conformable with overlying unit in the western and distal parts of the shelf (Figure 4-5). In the northern part of the study area, where the base of the seismic sequence 2 has a gentle dip towards the west, SS 2 makes up a substantial part of the Naust Formation (Rise et al., 2005) on Shelf. Extensive progradation occurred; most of the present day shelf was formed during the SS 2 period. In the Haltenbanken region the palaeo-shelf edge of SS 2 is only 30-50 km east of the present day shelf break.

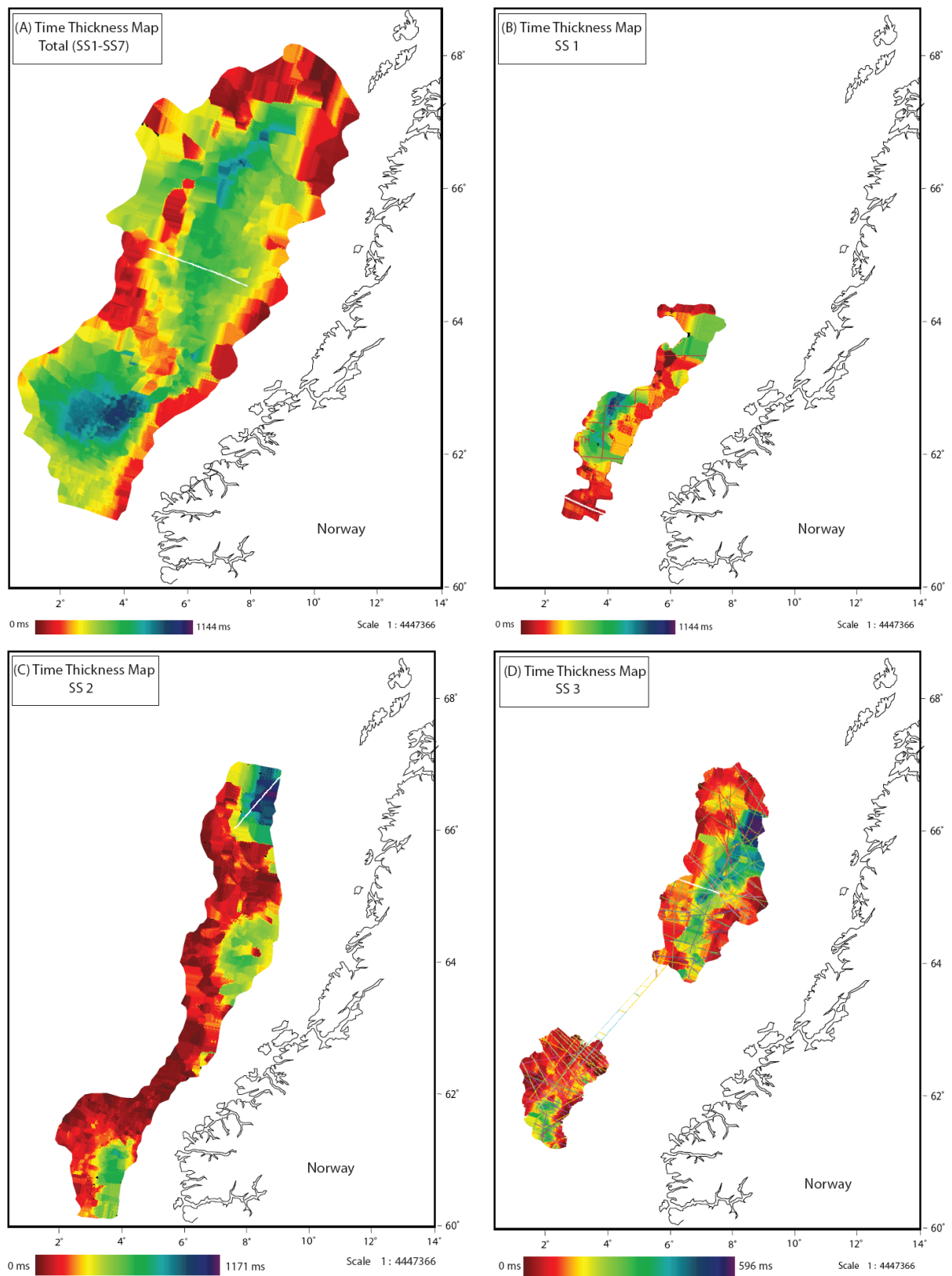
The sequence comprises numerous low-angle, wedge-shaped prograding depositional units. Some angular unconformities occur within seismic sequence 2 in the central-eastern part of the shelf, showing cycles of strong erosion, and the seismic character indicates very active and possibly varying depositional systems (Rokoengen et al., 1995). The inferred palaeo-shelf surfaces have subsided more in the west than in the east through time, and thus show a decreasing westerly dip towards younger ages (Figure 4-5). Most of the clinoform units down-lap on the base Naust horizon. Seismic sequence 2 apparently pinches out against the eastern flank of the Helland Hansen Arch and other domes farther north, but reappears on the western side of these domes. The thickest sediments occur in the northernmost part (1400 ms twt), near outer Trænadjupet (Figure 4-6 C). West of Møre (Frøyabanken–Langgrunna), the basin is much deeper, resulting in steeper dip angles. The sheet like units in this area

commonly show an aggrading pattern as sediments were dispersed towards the deep part of the Møre Basin. The time thickness of seismic sequence 2 is commonly less than 250 ms twt, showing a limited progradation of the Møre shelf and margin (Figure 4-6). In the northern part of the Storegga Slide area, thick slide deposits constitute the upper part of the sequence, showing that the area was slide-prone also in the early Naust period. Although the sequence reaches a time thickness of 400 ms twt at the North Sea Fan, it comprises only 20–30% of the Naust Formation in this area.

4.2.3. Seismic sequence 3 (SS 3)

The seismic sequence 3 (SS 3) has been interpreted as a package of sediments bounded at the base by seismic surface UCS 1 (unconformity clinoform surface) and seismic surface UCS 2 on top. The seismic sequence boundary UCS 1 has been defined by the clear toplap truncations formed by erosion of the topsets of the clinoforms of seismic sequence 1. This can be clearly seen on seismic line GMNR-94-310-AA (Figure 4-5). The sequence surface UCS 1 is an erosional surface in the eastern and middle part of the shelf but turns to become a conformable surface in distal basinwards parts of the basins. It has been mapped both north and south of the study area on the basis of the same criteria, as mentioned above, but the linkage of this sequence boundary through the Storegga Slide area is sometimes questionable. The seismic quality does not permit to trace or correlate this boundary across that area with confidence. Stratigraphical position and tie point from crossing lines have been used as guide line for connecting this surface on both sides; therefore the interpretation through the Storegga slide area is open to discussion.

This sequence comprises low-angle, parallel to sub-parallel wedge-shaped prograding depositional units with their maximum thickness in middle part and decreasing towards land and sea. Thickness of this seismic sequence varies from south to north, while its lateral extension is more linear and follows a confined path (Figure 4-6D). Maximum thickness of this sequence is observed south east of Vøring Basin, west of the Nordland Ridge. In the south, the seismic sequence is thicker in the southern parts of Møre South.



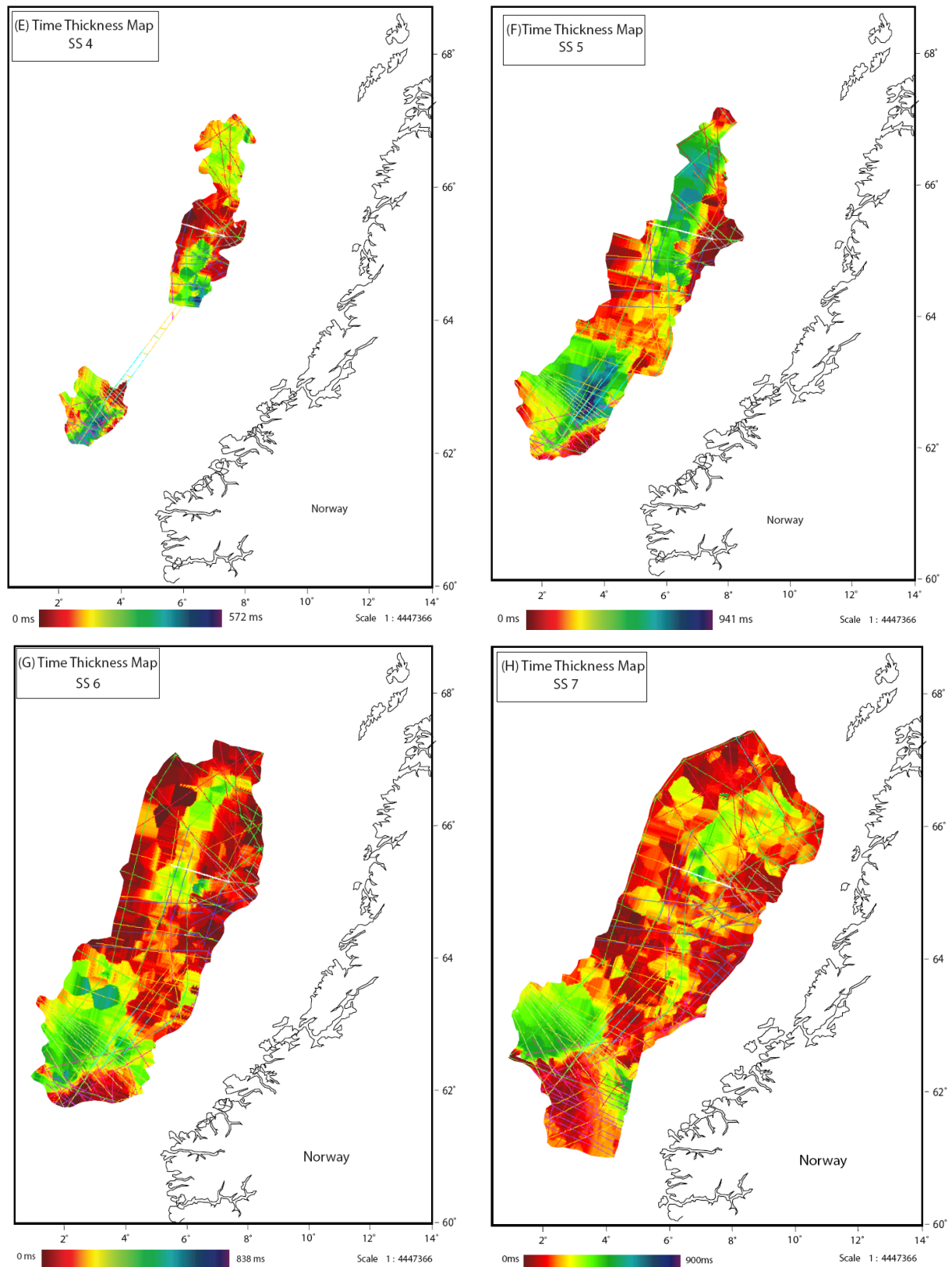


Figure 4-6: Time thickness maps (two way travel time) of: (A) total Plio-Plietocene prograding wedge ; (B) SS 1 seismic sequence 1, (C) SS 2, (D) SS 3, (E) SS 4, (F) SS 5, (G) SS 6, and (H) SS 7. Note that the sediment thicknesses in southern area increase towards younger ages.

4.2.4. Seismic sequence 4 (SS 4)

The seismic sequence 4 (SS 4) has been interpreted as a fourth seismically defined unit of the Plio-Pleistocene prograding wedge system. The sequence is bounded on the base by the unconformity clinoform surface UCS 2 and unconformity clinoform surface UCS 3 on the top.

The UCS 2 sequence boundary is characterized by erosional toplap truncation of clinoforms in the underlying seismic sequence 3 in the eastern and middle part of the shelf. The boundary turns to be a conformable seismic surface in the basinward parts of the basin (Figure 4-4, and 4-5). The surface finally laps against the Helland–Hansen Arch. The erosional truncation gives rise to a regionally mapable surface which turns into a timeline in distal parts of the basin.

Seismic sequence 4 comprises low-angle, parallel to sub-parallel wedge-shaped prograding clinotheme units with maximum thickness in the middle part of the sequence and decreasing both landward and basinward. The topsets of these gently inclined clinothemes appear to have been eroded while the rests of their geometrical elements are well preserved. This seismic sequence has more or less the same geographical distribution as seismic sequence 3, but it is distributed slightly more basinwards than SS 3. The northern depocenter of the unit probably had ~550 ms twt thickness and is located in the outermost Trænabanken and west of Sklinnadjupet. The maximum thickness is observed in Møre South, whereas the thickness of SS 4 reaches almost zero in the Storegga area. In the northern part of the study area SS 4 has little thickness, but its lateral distribution is greater than compared with that in the southern area of occurrence (Figure 4-6E). Most of the thicker parts are located in the eastern Vøring Basin. It also has some thicker portions in an area just west of the Trøndelag Platform. The linkage of UCS 2 through the Storegga area was almost impossible, so the correlation of this seismic stratigraphic surface across this area of mass wasting has been left un-interpreted and open to discussion.

4.2.5. Seismic sequence 5 (SS 5)

Seismic sequence 5 (SS 5) comprises several initially prograding, later aggrading or slope-building, units. The sediments probably represent several glacial-interglacial cycles. SS 5 has been defined by the bounding seismic surfaces, UCS 3 at its base and UCS 4 on its top. Unconformity clinoform surface 3 is characterized by erosional truncation of the underlying

clinoforms of SS 4 in the middle and eastern parts of its area of presence, and it is a conformable surface in the westward parts of the basin. This seismic surface seems to continue over the Helland–Hansen Arch but with lesser confidence in interpretation. Maximum deposition occurred along the present shelf edge, and locally slightly west of it (Figure 4-6F). The northern depocenter probably has ~600 ms twt thickness, is located in the outermost Trænabanken and west of Sklinnadjupet. The units deposited on the slope of this area appear to be acoustically incoherent, and many of them are fairly thick. Some clinoform units thin down-slope, and pinch out on the middle-lower slope. Other units are of fairly even thickness, or may thicken in the lower part of the slope.

The upper part of sequence SS 5 almost completely covers the Helland–Hansen Arch (Figure 4-5) and other dome structures farther north. On the middle–lower slope west of Haltenbanken, some units of stratified sediments occur between more acoustically incoherent units, one of them being up to 70 ms twt thick. North of the northeastern corner of the Storegga slide area, seismic sequence 5 comprises many thin sheet-like, acoustically incoherent units that commonly pinch out on the mid-slope and inter-finger with succession characterized by internal parallel reflectors. The depositional environment in the Storegga slide area is complex, with glacial debris, slide deposits and stratified sediments (Stoker et al., 2005). On the North Sea Fan, sediments up to 600 ms twt in thickness were deposited during the seismic sequence 5 period (Figure 4-6F).

4.2.6. Seismic sequence 6 (SS 6)

The seismic sequence 6 (SS 6) is bounded at the base by the seismic surface UCS 4 (unconformity clinoform surface) and by the upper regional unconformity (URU) on its top. Unconformity clinoform surface 4 is characterized by erosional truncation above clinoforms in underlying SS 5 in the middle part of its area of occurrence along the coast, whereas the UCS is developed more as a conformable surface in the distal parts of the basin, beyond the Helland–Hansen Arch. The erosional truncation in the middle part of this sequence boundary is less pronounced in the southern area of occurrence compared with the northern areas; this indicates that the amount of sedimentation and erosion varied considerably along the entire margin at the time when this seismic sequence was formed.

The seismic sequence 6 comprises most of chaotic seismic reflections, probably due to clay and mud dominated sediments. Some reflectors are still traceable and are stacked on each

other in an aggrading looking pattern. The seismic sequence 6 is completely absent in eastern parts of study area, both south and north of the Storegga slide area, but it has considerable lateral distribution in the middle and western parts (Figure 4-6G). Maximum thickness of this package is present in the Møre Basin, whereas its continuity through the Storegga slide area is good with thickness of about 300 ms twt. Towards the northern depocentre this sequence is thickest in south-eastern part of the Vøring Basin with a thickness reaching as much as 400 ms twt. It is possible to trace this unit beyond the Helland–Hansen Arch with greater degree of confidence because of the decreased doming effect at this level.

The seismic character of SS 6 varies from good in the middle south to chaotic in far northern parts of the study area. It is suggested that pelagic to hemipelagic sediments dominate in this unit (see discussion chapter for details).

4.2.7. Seismic sequence 7 (SS 7)

The seismic sequence 7 (SS 7) is the last and youngest seismically defined sequence of the Plio-Pleistocene prograding wedge system and comprises aggrading depositional units. Seismic sequence 7 is bounded at its base by the upper regional unconformity (URU) and by the sea bottom on the top. The upper regional unconformity is a regional seismic surface, characterized by pronounced erosion on the eastern parts throughout the study area, whereas in the middle parts there is still noticeable erosion but less than in the eastern part. This seismic surface seems to have eroded quite significant parts of older sequences. Due to this marked erosion and development of resulted angular unconformity, it is relatively easy to identify this surface in study the area, with exception of the Storegga slide area where seismic quality does not allow picking it easily.

Depositional architecture within SS 7 changes from progradation to aggradation across the upper regional unconformity in most parts along the Norwegian Continental Margin; the exception is again the Storegga slide area where the reflector stacking pattern is not preserved. The aggradation pattern is very prominent on the southern and landward part of the occurrence area of SS 7. However, some evidences of low-angle progradation can be seen in the northern part of the study area but aggradation is still the dominant depositional style as seen from the reflector configurations. The aggradational pattern indicates limited sediment input directly from land areas in the east in comparison with creation of accommodation space (see further discussion below).

Seismic sequence 7 is thickest in the southern half (particularly in the Møre Basin) of the study area where its thickness reaches as much as 450ms twt; the thickness gradually decreases towards the north but the thickness increases slightly again in the area west of the Nordland Ridge (Figure 4-6 H).

4.3. Chronostratigraphic charts

Two chronostratigraphic charts are constructed in this study and are presented in Figures 4-7 and 4-8. These are based on seismic interpretation of two of the type sections BB' and DD' (shown in Figures 4-3 and 4-5). They were made to obtain better insight into the time relationships of the depositional systems, and their relationships to surfaces of non-deposition, condensation and erosion. Seismic reflections considered to represent time lines have been plotted in order of age, with an equal time increment given to each horizon, because there exist limited knowledge about the absolute age of horizons.

Figures 4-7 and 4-8 show the distribution of the seismic sequences in time and space. Several periods of interglaciations have been shown. These are the periods of relatively warmer climate, when the glaciers retreated. Within seismic sequence 2 and some times in 5 there can be several other smaller periods of inter-glaciations but because of the lack of time only the prominent ones have been mapped and shown here. Seismic sequences SS 1 to SS 6 are genetically related to each other but seismic sequence SS 7 is not related to other sequences. SS 7 marks the end of glacial advancement and also marks the end of regional tilting. The blank area on the right side of the SS 1- SS 7 represents the time gap for upper regional unconformity (URU). On the left side of the sequences the blank area represents the areas of non deposition or condensed sections. These condensed sections on seismic sections appear to die out but in fact they are not dieing out, rather their thickness is below seismic resolution. Note that seismic sequence 1 is not available in northern part (Figure 4-8). In northern parts a similar sequence (known as Molo Formation) is present but if it is exactly the same as SS 1 is not yet known (see discussion for more detail on it).

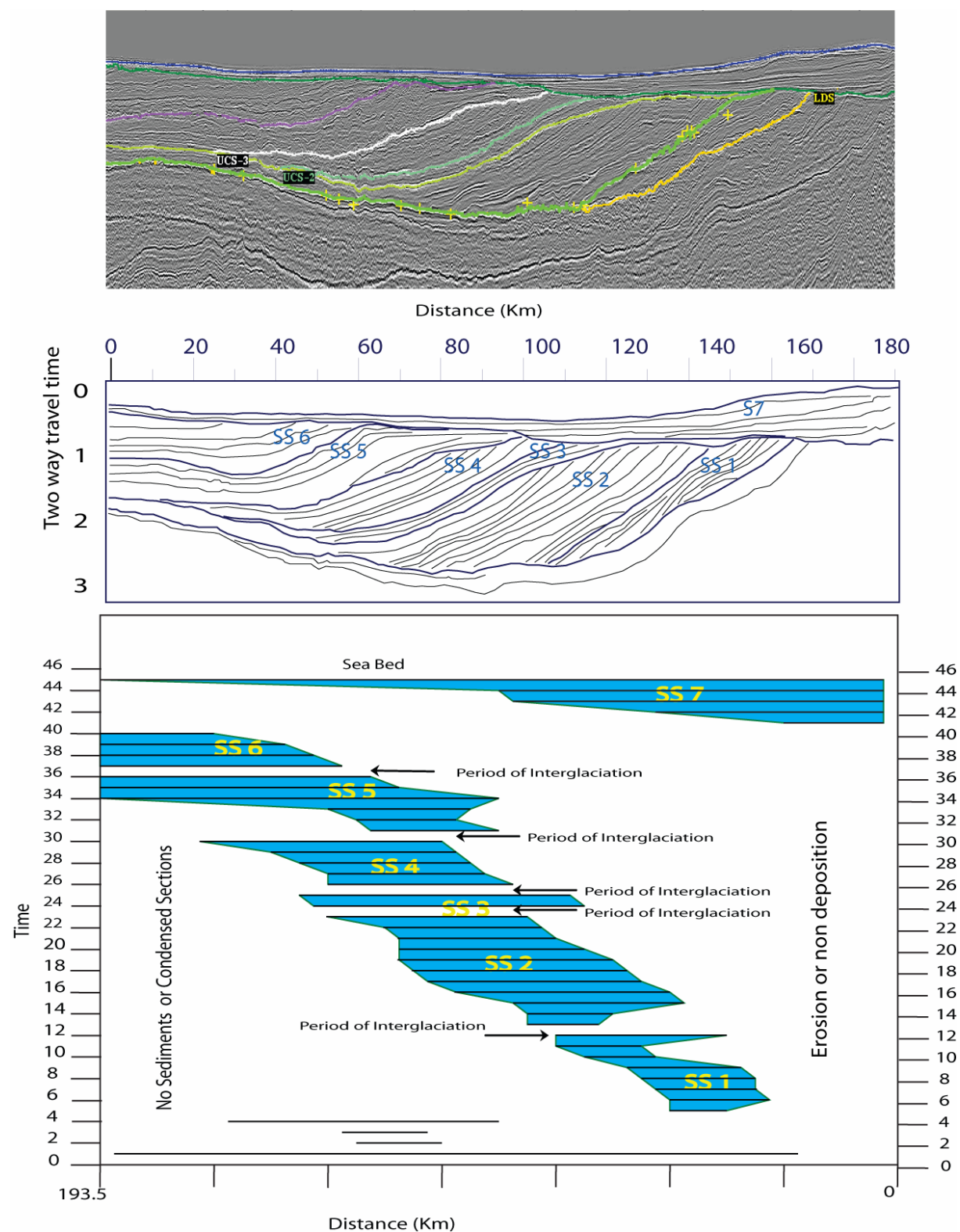


Figure 4-7: Chronostratigraphic (Wheeler) diagram of the type section BB' derived from seismic data covering the Plio-Pleistocene of mid-Norway, showing the relative age and distribution of the sequences

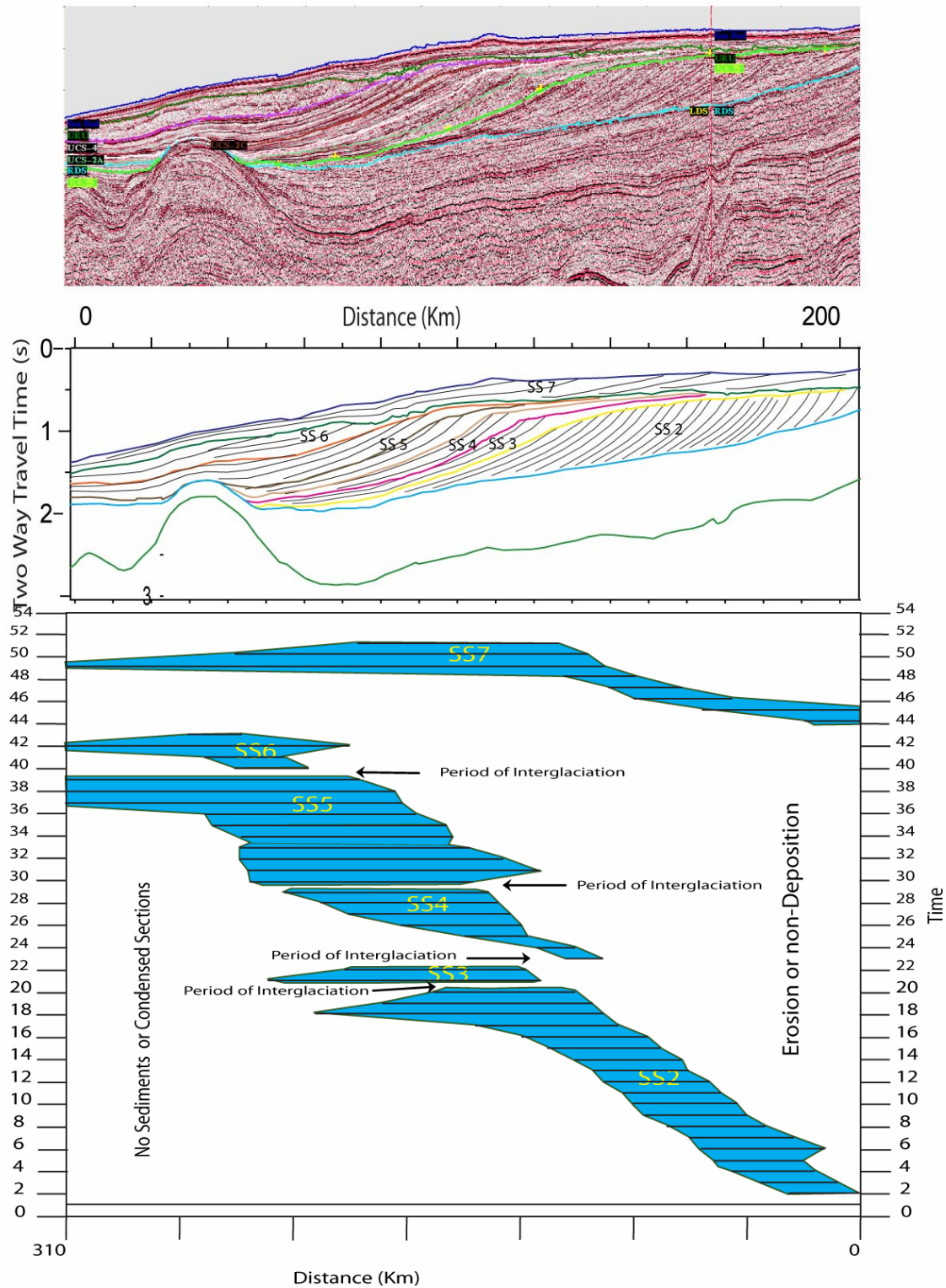


Figure 4-8: Chronostratigraphic (Wheeler) diagram of the type section DD' derived from seismic data covering the Plio-Pleistocene of mid-Norway, showing the relative age and distribution of the sequences.

4.4. Seismic Facies Analysis

Five seismic facies categories have been interpreted from seismic reflection data. No published seismic sedimentary facies studies on the Plio-Pleistocene strata of the mid

Norwegian Continental Margin have been found so far. The seismic facies classification is based on internal reflector configuration, external geometry of surface-bounded seismic facies, seismic reflectivity and continuity. These geometrical relationships characterize the five seismic facies categories described in this section. Hence, the classification scheme (table) is based on general publications of seismic facies analyses and analogue studies. The analogue studies are, especially from the Gulf of Mexico (Mitchum et al., 1977; Vail et al., 1977; Weimer, 1990). There is no unequivocal link between seismic facies and depositional systems, with the probable exception of the link between clinothems and slope systems. (Sangree and Widmier, 1977) listed seismic facies with their geological interpretation; however, without well control this link is generally considered tenuous (Emery et al., 1996).

Table 4-2: General seismic facies, according to (redrawn from Mitchum et al., 1977).

Facies characteristics	Facies	Interpretation of depositional framework
<ul style="list-style-type: none"> • High reflectivity, parallel to sub-parallel facies 	1	Shelf to shelf margin and prograding slope
<ul style="list-style-type: none"> • Low-reflectivity, commonly continuous, sub-parallel to convergent reflectors 	2	Prograding slope
<ul style="list-style-type: none"> • Prograding clinoforms 	3	Shelf margin and prograding slope
<ul style="list-style-type: none"> • Chaotic facies 	4	Mass-transport slump and creep, fluidized sediments, and generally gravitational collapsed deposits
<ul style="list-style-type: none"> • Onlapping-Fill seismic facies 	5	Basin slope and basin floor

The choice of analogue studies has been done based on recognizable seismic facies configuration compared with the seismic facies pattern recognized in this study. Hence, the mentioned analogue studies have been used, especially, to compare the seismic facies groups A, B, C.

Horizontal and vertical seismic resolution constrains the sizes of recognizable depositional geometries in seismic data. Both vertical and horizontal aspects of seismic resolution are a function of acoustic pulse frequency, pulse wavelength, and layer velocity (Neidell and Poggiagliolmi, 1977), as high frequency energy is absorbed and pulse wavelength increases. At depths of several thousand meters, pulse mid-frequency may decrease to 25-30 Hz,

generating wavelengths of about 100 m. Based on the general rule that resolution reaches the limit at $\frac{1}{4}$ wavelengths, minimum vertical resolution of a succession is about 25 m. For example, it is possible that sand intervals of a few meters thickness, as example small channel/levee units, will not be resolved on seismic sections. Because the sediment outbuilding has taken place far into the distal parts of the basin in the study area, strata get very thin and can have thicknesses below seismic resolution. This may result in apparent termination of these reflectors against younger reflectors. So, seismic resolution is therefore important to consider when it comes to seismic facies analysis.

On the basis of reflection configuration, seismic facies has been defined into three major categories, namely; (A) parallel to sub-parallel facies, (B) prograding clinoforms facies and (C) chaotic facies. These facies categories are further divided into subcategories and are described below. In addition, the seismic facies 4 and 5 are defined as facies categories (D) and (E), respectively.

4.4.1. Seismic facies category A, parallel to sub-parallel facies

The seismic facies category A consists of high reflectivity continuous parallel reflectors. This seismic facies category ranges in some areas from thin, single seismic wavelets to more complex waveforms expressed as doublets or broad, complex, high amplitude sets or troughs and peaks (Figure 4-9).

The seismic facies category A is interpreted to be related to fine-clastic sub-marine fan/sheet deposits with interbedded pelagic to hemipelagic clay. This combination of sub-marine fan deposits and pelagic to hemipelagic sediments is probably responsible for the high amplitude of these seismic facies. The interpreted depositional environment for this seismic facies category is based on comparison with analogue seismic studies (Sangree and Widmier, 1977). It is however, difficult to decide whether the seismic facies A category represents basin floor fan or slope fan, due to little knowledge about the depositional surfaces.

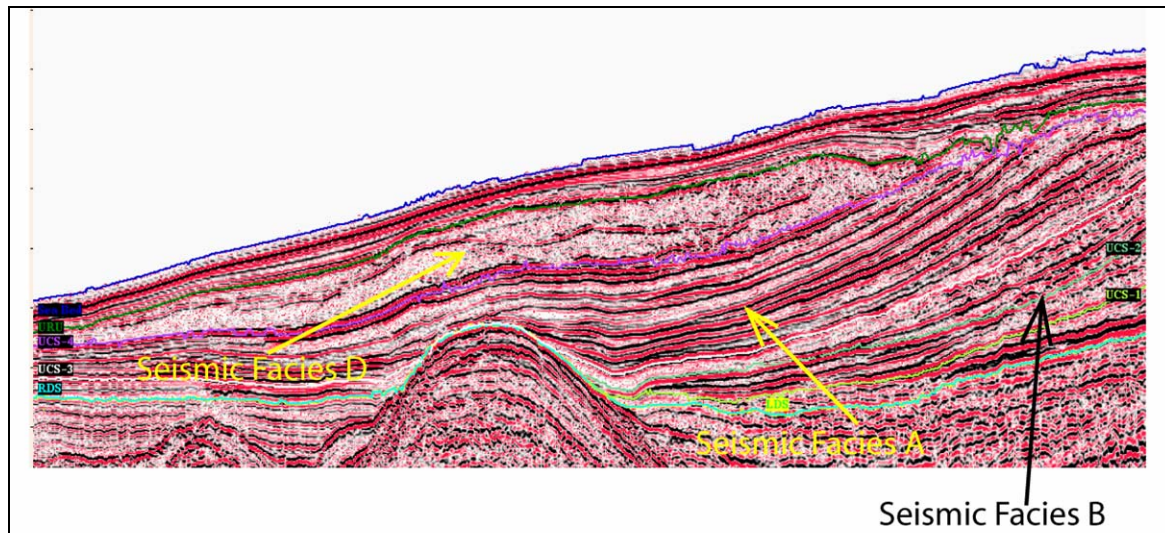


Figure 4-9: Seismic section showing seismic facies category A, seismic facies category B and seismic facies category D.

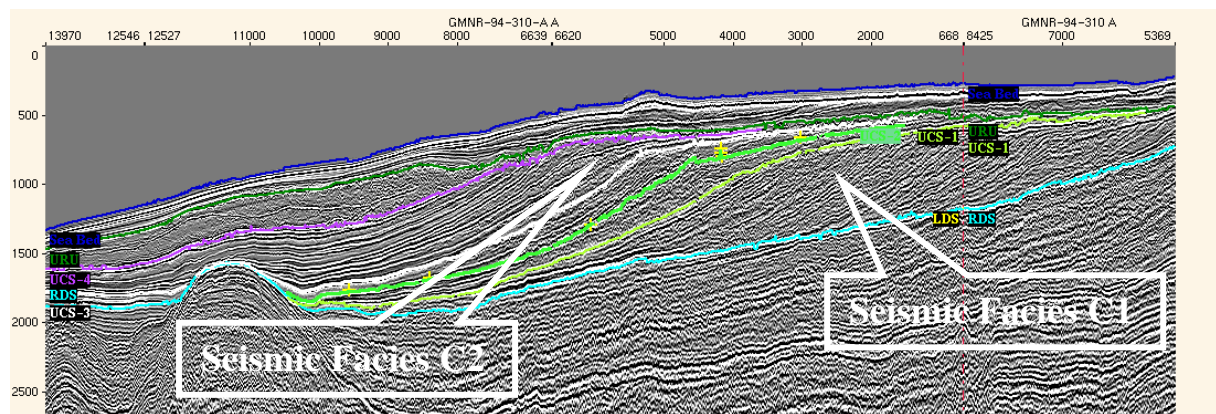


Figure 4-10: Seismic section showing seismic facies category C and seismic facies category E. The seismic facies category A pattern is recognized in three main areas; south-west, north-west and in distal parts of the basin. A gently progradational seismic pattern of seismic facies category A is recognized in the western parts of the seismic lines GMNR-94-105A and 001-VBT-94-A. Seismic facies category A is widely distributed throughout the western parts of study area and belongs to seismic sequences 5 and 6 with an exception of the Storegga slide area, whereas this facies category is almost absent in eastern and landward areas. In terms of vertical thickness stratigraphical units characterized by this seismic facies A category, thickness map of seismic sequence 5 and 6 can be used as analogues.

4.4.2. Seismic facies category B, sub-parallel to convergent facies

Seismic facies category B consists of low reflectivity, commonly continuous sub-parallel to convergent reflectors (Figure 4-9). Seismic facies category B occurs in close association with seismic facies category A, and is thought to be related to the interbedded sediments within

stratigraphic units otherwise characterized by seismic facies category A, especially where the distance between areas of these two facies categories is relatively narrow.

Seismic facies category B is interpreted to represent hemipelagic and mud rich deposits between sub-marine lobe/fan deposits characterized by seismic facies category A. (Sangree and Widmier, 1977) suggested a similar interpretation for seismic pattern characterized by sub-parallel to convergent reflectors with poor to fair continuity. The low amplitude reflectors of seismic facies category B suggest either that the actual stratigraphic interval is thin-bedded or the sediment composition dominated by one particular lithology.

4.4.3. Seismic facies category C, prograding clinoforms

The major seismic facies category recognized in this study is prograding clinoforms, here defined as category C. Three principal reflection configurations have been recognized within the prograding clinoform facies category B. These are the C1 oblique progradational reflectors, C2 sigmoid progradational reflectors and C3 shingled seismic reflectors. They are all characterized by downlapping reflections at their base.

C1 Oblique prograding reflectors

The C1 oblique prograding reflector category is distinguished by its prominent oblique reflection configuration when viewed parallel with depositional dip. Reflectors are terminated by toplap at or near the upper surface (Figure 4-10) and by downlap at the base. Downlapping reflector terminations represent outbuilding of sediments from relatively shallow into relatively deep water with thinning of outer toes of individual beds, commonly with thickness below seismic resolution (Sangree and Widmier, 1977).

The oblique prograding facies category C1 is the most prominent and widespread seismic facies category which is recognized in most parts of the study area. Seismic sequences SS 1, 2, 3 and some times SS 4 are characterized by this particular category of seismic facies (Figure 4-3 and 4-5). Low-amplitude zones in seismic sequence SS 3 indicate either beds too thin to be resolved by seismic methods or a zone of one predominant lithology type. Based on the regional geological knowledge of the area under consideration and geometrical position of seismic stratigraphical units dominated by this particular seismic facies category, it can be suggested that the facies category C1 is more like to be sand or/and coarse-clastic prone than shale prone. Units of this seismic facies category are interpreted to have been deposited on the

shelf margin by fluvial to glaciofluviomarine deltas or/and ice-margin deposits in relatively high energy depositional systems. (Sangree and Widmier, 1977) suggested a similar interpretation for seismic pattern characterized by oblique prograding facies with fair reflection continuity. Parallel with depositional strike, reflection are sometimes parallel and even show low angle oblique or sigmoid patterns.

Amplitude, continuity, and cycle breadth vary at different positions depending upon the position and angle in the oblique configuration. Clinoform zone reflections are variable, but show a general decrease in continuity and amplitude from upper clinoform to lower clinoform.

C2 Sigmoid-progradational reflectors

The C2 sigmoid progradational facies category is characterized by gentle sigmoid shape reflections along depositional dip. The reflections downlap basinward and is concordant with the top of the unit in landward direction.

Sediments of this facies category are generally interpreted to have been deposited on the slope along continental margins with topsets extending into shelf-margin areas (Sangree and Widmier, 1977). The facies category has been observed in this study area to be characterized by moderate to high amplitude reflectors.

The seismic sequences 3 and 4 in the northern part of the study area and the seismic sequence SS 5 in the southern parts of the study area are all characterized by this kind of seismic facies category (Figure 4-3, 4-5). High continuity of reflections suggests continuous strata deposited in a relatively widespread and uniform environment, and high reflection amplitude may indicate interbedding of shales with relatively thick sandstone or siltstone types of sediments. Thickness maps of seismic stratigraphic units having the C2 seismic facies category can be used to infer the vertical and lateral distribution of these facies in the study area (Figure 4-10). Commonly the C2 sigmoidal prograding facies category units show lensoid forms, elongated parallel with depositional strike, onlapped by various seismic units of various kinds of chaotic facies. The internal reflection configuration and external form of C2 sigmoidal facies units suggest a relatively low energy depositional environment for them.

C3 Shingled seismic reflections

The C3 shingled seismic facies category units are characterized by parallel upper and lower boundaries and with gently dipping parallel oblique internal reflectors that terminate by apparent toplap and downlap. The facies category is characterized by high amplitude and

good reflector continuity. Successive oblique internal reflectors within the units show little overlap with each other. The overall pattern resembles that of parallel oblique progradational configuration, except that the thickness of the units with this seismic facies category is just at the point of seismic resolution of the oblique beds.

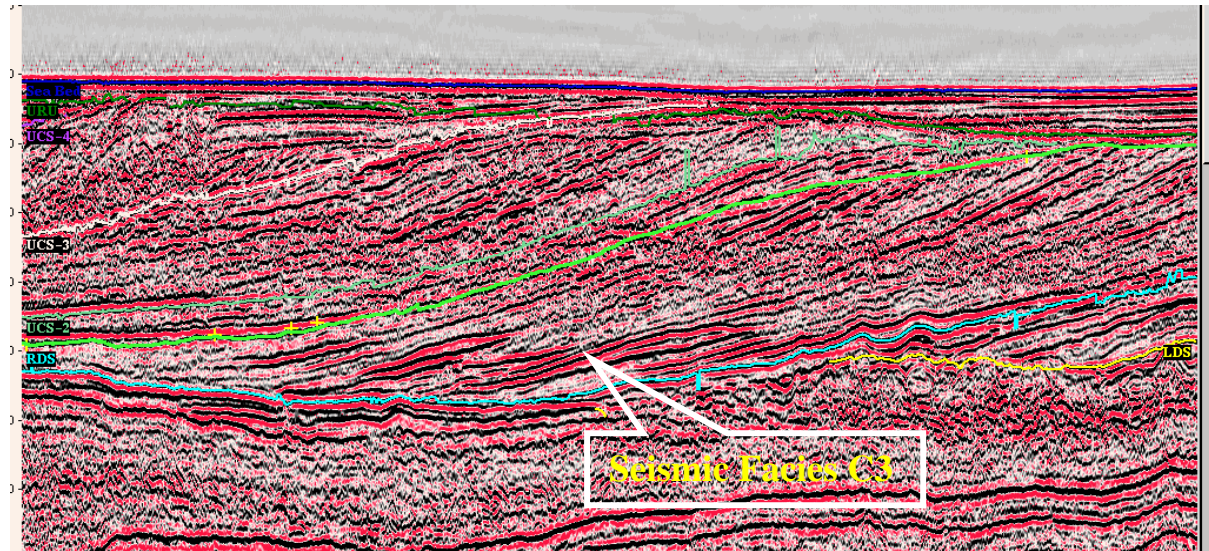


Figure 4-11: Seismic section shows seismic facies category C3.

The C3 shingled seismic facies category has been mapped mainly in southern parts of Møre South and in other parts of the southern areas where it belongs to the seismic sequence SS 2 (Figure 4-11) and are located as bottom sets of progradational clinothem. Elsewhere in the study area units of these kind of seismic facies category are recorded in various parts of the Plio-Pleistocene prograding wedge system but are less prominent and with limited distribution.

Shingled seismic facies has been interpreted as depositional units prograding into shallow water (Mitchum et al., 1977). Their abrupt disappearance can be interpreted as thinning of these units below seismic resolution.

4.4.4. Seismic facies category D, Chaotic facies

Seismic facies category D consists of seismic facies 4 characterized by very low reflectivity, low amplitude, poor reflection continuity, and almost no internal reflection configuration (Figure 4-9). Reflection amplitude, continuity, and frequency seem to reflect the extent of homogenization in mass transport types of these chaotic units. Chaotic seismic facies units are generally characterized by mounded external form, by location in topographic lows, and by an internal pattern of contorted and discordant to wavy sub-parallel reflections (Sangree and Widmier, 1977). These facies are common features in distal parts of the most of seismic lines

parallel to sedimentary dip. Below the regional downlap surface (RDS), these facies are extensively present, particularly in southern parts of the study area. As successions below RDS are not included in this project, the chaotic facies below RDS have not been mapped three dimensionally.

In western parts of the study area the chaotic seismic facies belongs to seismic sequence SS 6 (Figure 4-6). In the middle parts of the study area, which, is dominated by Storegga slide area, most of the seismic sequences are dominated by chaotic facies. So, it is therefore difficult to make a good relationship between chaotic facies and a particular depositional environment. Mass-transport processes like slide, slump, creep, fluidization and high-energy turbidity current processes are thought to be responsible for transportation and deposition of this facies (Sangree and Widmier, 1977). This mechanism fits well within Storegga slide area, but within seismic SS 6 this mechanism is more ambiguous in distal parts of the study area.

4.4.5. Seismic facies category E, Onlapping-fill seismic facies

Onlapping-Fill seismic facies consists of more uniform, parallel to gently divergent reflector pattern with high continuity and high to variable amplitude. Vertical and lateral gradation and interbedding with other fill facies have in other areas been observed to be common for this facies category (Mitchum et al., 1977; Sangree and Widmier, 1977).

Seismic stratigraphic units with the onlapping-fill seismic facies have been observed in the north-eastern parts of the Helland–Hansen Arch in the northern part of study area (Figure 4-12). This facies has limited distribution as the combination of domal structures like the Hellan– Hansen Arch and onlapping reflection configuration is of limited extent.

The onlapping nature and tendency to fill lows suggest that the onlapping fill facies represents strata deposited by gravity controlled flows along the bottom. Parallel patterns of continuous reflections created by widespread parallel strata are probably the expression of deposits formed by relatively low velocity turbidity currents interbedded with hemiplegic and pelagic deposits (Mithum et al 1977). On a broader scale, the onlapping-fill seismic facies is interpreted to indicate basin slope and basin floor depositional environment.

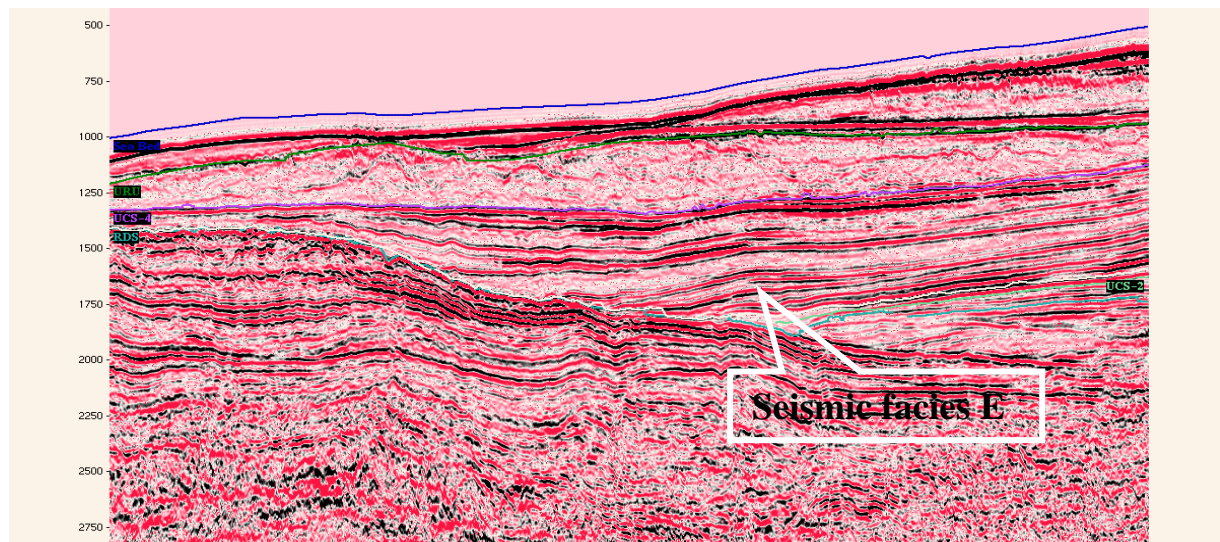


Figure 4-12: Seismic section showing seismic facies category E.

5. Discussion

5.1. Ages of the sequences

Ages of regional seismic surfaces like RDS, URU and of some other seismic horizons have been adopted from (Eidvin et al., 1998; Rise et al., 2005). The ages for the seismic sequences in between these regional surfaces have been assigned using relative age criteria, as there exist no well and biostratigraphic data to give exact ages. If the age suggested by Eidvin et al., (1998) for SS2 is correct (>2.3 My), the sediment supply to the northern shelf areas must have been extremely high in the period c. 2.7–2.3 Ma (Figure 5-1). Only a very strong Neogene uplift phase directly before and during this period, combined with frequent and large ice sheets eroding weathered bedrock and loose Tertiary sediments, could possibly explain this. In comparison, the accumulation rate in the period 0.4–2.3 Ma (SS4 and SS5) must have been

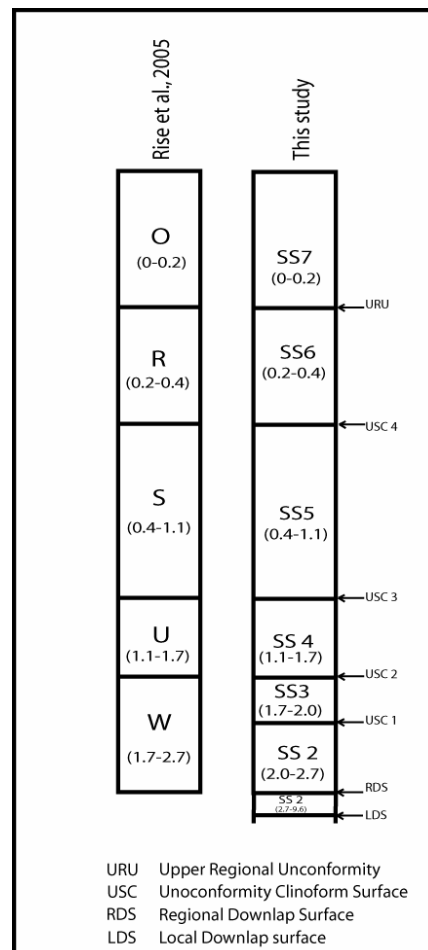


Figure 5-1: Diagram of the defined sequences and horizons in the Plio-Pleistocene prograding wedge, mainly based on the stratigraphy applied in Ormen Lange area (redrawn and modified from Rise et al., 2005). The proposed ages for SS 1, SS2 and so on till SS 7 are uncertain

very low. Similarly, it must also have been very low compared to the last 0.4 m.y. (SS6 and SS7). Evaluation of the ages based on different data sets reveals a c. 1 m.y. discrepancy with the previously defined horizon TND (located within SS5) (Eidvin et al., 1998). Thus, at present, ages cannot confidently be assigned to the sequences, at least to the three oldest. As previously mentioned, SS2 is likely to be much older than 1.1 Ma, and the uppermost part of sequence SS5 appears to be younger than 0.78 Ma (relative dating).

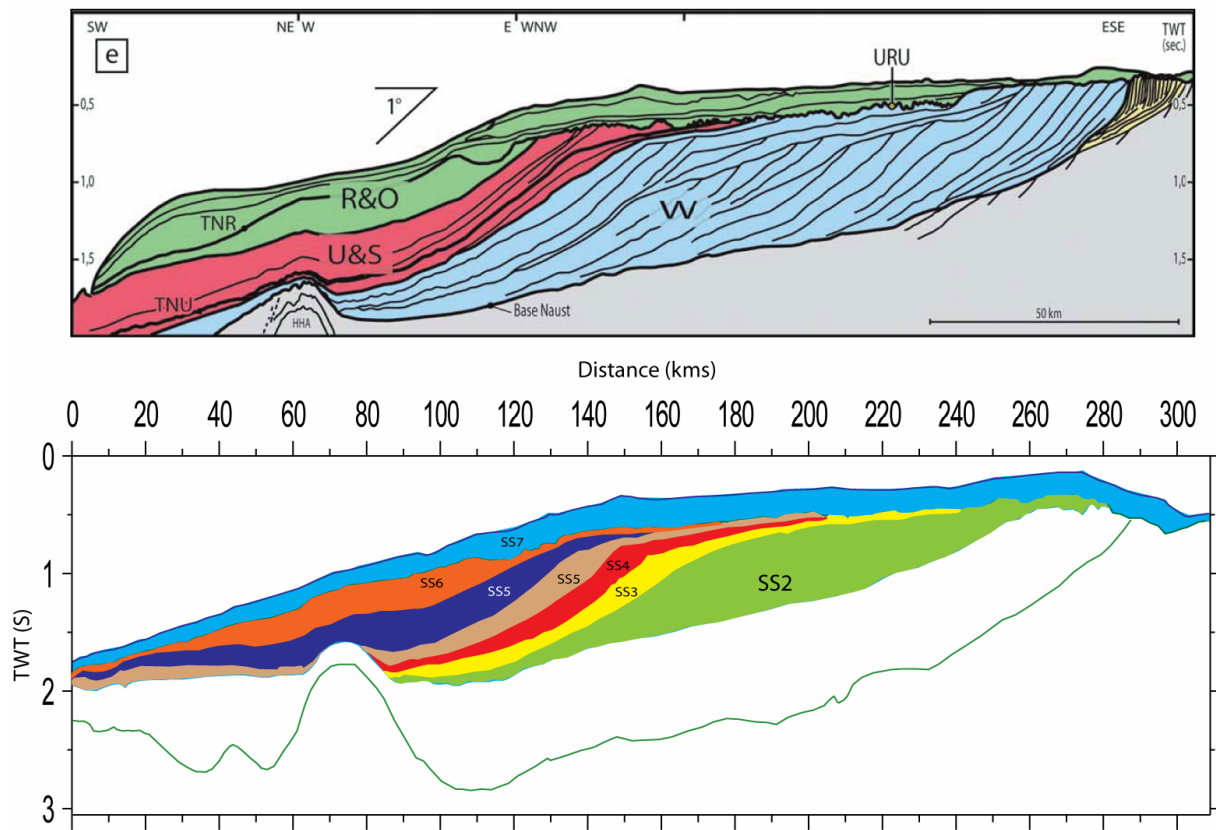


Figure 5-2: Comparison between seismic stratigraphic subdivision of Plio-Pleistocene prograding wedge on seismic sections (e) by Rise et al., (2005) and lower (this study), in northern part of study area.

5.2. Controlling factors

The fundamental issues in sequence stratigraphic models include consideration of the interaction between sediment supply and changes in accommodation space. A number of factors interact in controlling depositional environments, such as climate, relief of drainage basin, water discharge, tide, waves, tectonic, and basin geometry (Coe et al., 2003; Emery et al., 1996); however the effects can be summarized in available accommodation space and sediment supply.

Geometry of sedimentary successions is the product of variation in rates of accumulation of sediments, eustasy, and tectonic movement (Kendall and Lerche, 1988). Occurrence and

geometry of marine strata is largely dependent on sediment supply and sea level changes, whereas continental deposition responds to a much broader spectrum of processes, both autocyclic and allocyclic. Marine sedimentary systems are to a high degree the product of sea level change and climate, since climate controls sediment supply (Coleman and Wright, 1975; Galloway, 1989; Shanley and McCabe, 1994). Terrestrial sedimentary systems are more dependants on climate than marine depositional systems, since climatic processes affect weathering, erosion, and fluvial hydrology.

Accommodation space available for potential deposition is created from eustasy, tectonics, and autocyclic processes. Autocyclic processes incorporate variations within the depositional system, such as compaction and subsidence from isostatic adjustment.

5.2.1. Creation and destruction of accommodation space

Late Cenozoic sediment outbuilding offshore mid-Norway reveals important information about how and when accommodation space have been created and destroyed through time and space along the mid Norwegian continental margin. Creation and destruction of accommodation space cannot be explained only by eustatic sea-level changes. Tectonics must have played a significant contribution to creation and destruction of accommodation during the Cenozoic along the Norwegian continental shelf. There was a significant uplift in southern Norway and also in mid-Norway in Late Eocene-Early Oligocene times, which was accompanied by a lowered eustatic sea level, followed by tectonic subsidence of the basin floor during (early) Pliocene times (Faleide et al., 2002; Jordt et al., 2000). The tectonic uplift of the hinterland area and subsidence of the basin area was accompanied by a dramatic increase in sediment supply, as a result of the onset of glacial erosion in mountainous areas. The most significant subsidence event took place during Pliocene time, coincident with a general eustatic sea-level fall (Jordt et al., 2000) (Figure 5-3).

This complex interplay, between tectonic uplift at the landward side and contemporaneous tectonic subsidence in the basin domains (also referred to as tilting) together with eustatic changes caused fluctuations in relative sea level and the resulting creation and destruction of accommodation space. The hinge line, or hinge zone, the axis of rotation, separating areas of tectonic uplift from areas of tectonic subsidence varied in position through time. Effects of large-scale regional subsidence in the NE Norwegian Sea region, differential compaction and

isostasy, together with rates of erosion and sedimentation are thought to have further refined the dynamic interplay between accommodation, erosion and sedimentation.

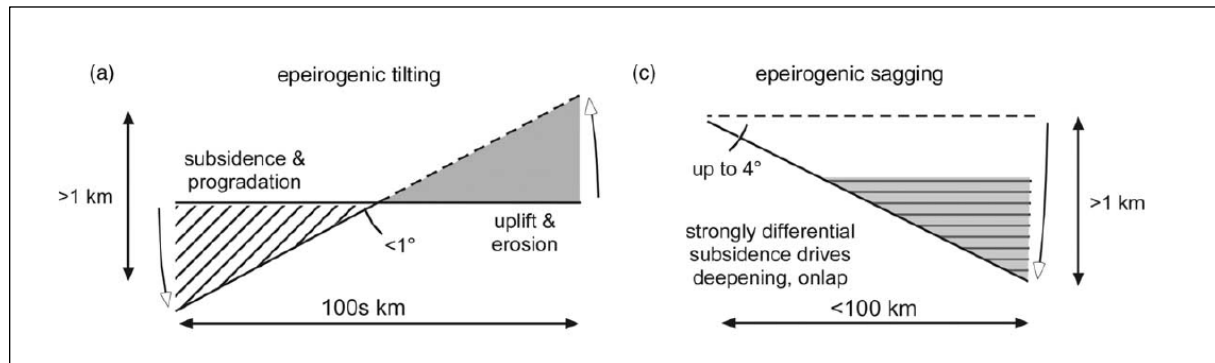


Figure 5-3: Inferred sedimentary responses to epeirogenic tilting (early and late Cenozoic) and sagging (mid-Cenozoic): tilting (coeval uplift and subsidence across hundreds of kilometres, rotations $< 1^\circ$) rejuvenated sediment supply and created space for basinward progradation of thick shelf slope wedges (Praeg et al., 2005).

The regional extent of eroded topsets and steepened foreset clinoforms within SS2 to SS5 illustrate how the hinge line of the shelf-hinterland tilting, was more or less parallel to the present day coast line. Tectonic uplift in the eastern hinterland side of the study area caused destruction of accommodation space and erosion in this area, whereas tectonic subsidence west of the hinge line formed accommodation space and deposition of sediments. The area or zone in which the hinging of tilting was located is considered to have acted as a bypass surface. Since the amount of tectonic uplift and subsidence have been changing through time and space, therefore, it is very difficult to pinpoint the location of the hinge line through time.

SS1 marks the onset of Late Cenozoic tectonic uplift and accompanying subsidence. Erosional surfaces within the upper parts of SS2 and SS3 is interpreted to have been triggered by tectonic uplift from tilting and carried out mainly by erosion from advancing shelf ice sheets. Topsets of SS4 and SS5 are suggested to have been eroded by recent glacial advancements (Rise et al., 2005) and are therefore not being related to tilting-related erosion. The geometry of SS7 marks the ending of this tectonic tilting, and the accommodation space for this unit is attributed to the combined effect of sea level change and glacial erosion by advancing ice sheets.

5.2.2. Formation of accommodation during events of glaciation

Pronounced erosion at the base of this aggrading unit (SS 7) seems to have been caused by glacial advancement far into the basin. (Rise et al., 2005) discussed the advancement of ice sheets into the basin as a possible mechanism for the erosion of large parts of topsets of prograding clinothems. Ice sheets were thick enough to be grounded and cause erosion. Due to this Pleistocene glacial erosion, the proximal parts of the Pliocene sequences have been removed and the sequences are therefore not complete.

Large ice sheets with capacity to advance far out onto continental shelves form during ice ages. This also implies that the eustatic sea level was lowered during the glacial period. An important issue related to the advancement of such ice sheets is how large enough accommodation space can have been formed for sediments to accumulate and even prograde during glacial time, even when the sea level was lowered glacio-eustatically. During the time of glaciation, the eustatic sea level falls, but the relative sea level may rise in areas where the rate of tectonic subsidence is higher than rate of fall in eustasy.

Sediment load of rapidly outbuilding clinothems seems to have played an important role in the subsidence of basin, particularly when the uplift related tilting was strongly waning. This sediment load driven subsidence seems to have contributed towards the rise in relative sea level. In terms of sediment supply, the role of the Norwegian Channel Ice stream is also very important. This ice stream transported enormous amounts of glaciogenic debris to the North Sea Fan during the last 3–4 glaciations (c. 400,000 years) (Figure 4-6). In comparison to the earlier phases, the Norwegian Channel Ice Stream became very important during the final phase of prograding wedge evolution (SS7 time) (Figure 4-6). The ice sheets and ice streams extended out to the entire shelf edge at several times during the last three to four glaciations and deposited significant volumes of sediment at the margin (Rise et al., 2005).

5.2.3. Accommodation space (A) vs sediment supply (S) in terms of offlap break trajectories

An offlap break trajectory is defined as a path of offlap break migration in a cross-sectional depositional dip view (Figure 5-3) and is a function of relative sea level changes, sediment supply and basin physiography (Helland-Hansen and Gjelberg, 1994) (shoreline trajectory is modified by offlap break). The direction of offlap trajectory is a useful basic concept for the

description of internal architecture of depositional cycles. For simplicity, three main classes of offlap break trajectories have been defined (Bullimore et al., 2005), which are as follows.

1. *Positive offlap break trajectory*

If the line obtained by joining the points of offlap break is rising upwards, as shown in (Figure 5-4) then it is defined as positive offlap break trajectory. Positive offlap break trajectory means that there were high rates of sediment supply and creation of accommodation. Steeper the angle of offlap break trajectory, higher will be the sediment supply and higher will be the rate of creation of accommodation space. Positive offlap trajectories are formed in prograding systems.

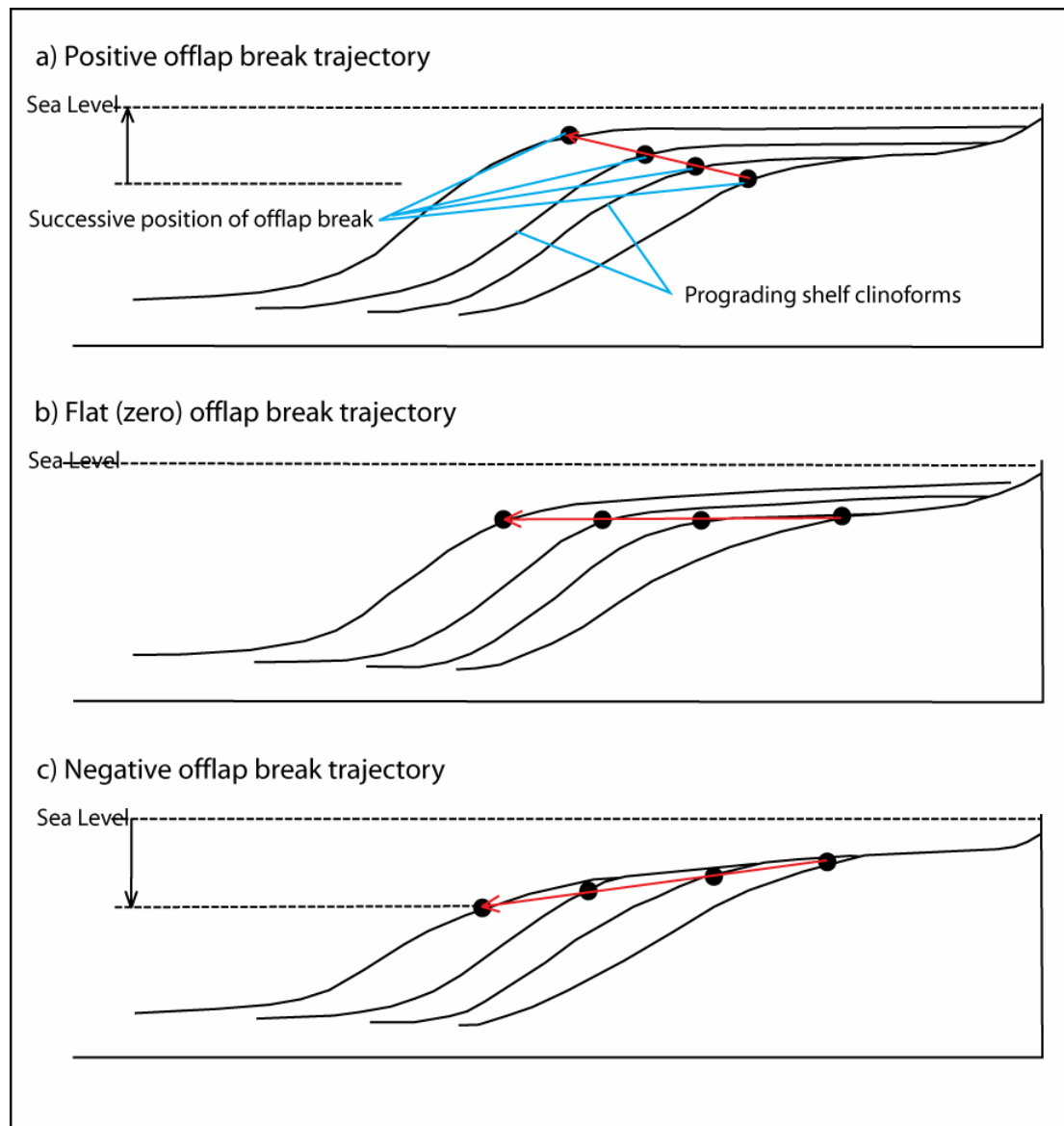


Figure 5-4: Schematic diagram showing the different scaled prograding shoreface and prograding shelf clinoforms. Note that the successive positions of the offlap break (black dots) allows for the identification of a offlap break trajectory. The offlap break trajectory is determined by the successive positions of the migrating shelf-slope break and may exhibit a) high angle positive trend; b) flat and c) negative (high /low angle) trend (Bullimore et al., 2005).

2. Flat (zero) offlap break trajectory

If the line obtained by joining the points of offlap break is more or less horizontal, as shown in (Figure 5-4) then it is defined as flat or zero offlap break trajectory. Flat offlap break trajectory means that rate of sediment supply and rate of creation of accommodation space were low and more or less equal. Flat offlap break trajectories are common in gently prograding to aggrading system.

3. Negative offlap break trajectory

If the line obtained by joining the points of offlap break is falling downwards, as shown in (Figure 5-4) then it is defined as a negative offlap break trajectory. Negative offlap break trajectory means that there were low rates of sediment supply and creation of accommodation space is negative. In this case actually no accommodation space is being created but progradation is the result of higher rates of sediment supply.

In the northern parts of the study area, the offlap break trajectories are slightly rising upwards from SS2, SS3 and SS4, so therefore, this is a positive offlap break trajectory. It means that there have been high rates of creation of accommodation and sediment supply during the deposition of SS2, SS3 and SS4. The trajectories from SS5 till SS7 are flat or zero, suggesting that rate of creation of A and rate of S were more or less equal and reduced by the time of deposition of SS 5 and SS 7 (Figure 4-3 and 4-5).

In southern parts of the study area the offlap break trajectories are gently raising upwards from SS1 till SS7 which means a positive trajectory for almost all the seismic sequences. The angle of inclination from SS1 till SS4 is very gentle and changes to slightly steeper from SS4 till SS7. Based on these variations in trajectory angle it can be interpreted that rate of creation of A and rate of S have been increasing through times in southern parts of the study area.

5.3. Evolution of large scale progradation

The evolution of Late Cenozoic outbuilding in the northern North Sea and off mid-Norway can be divided into three phases, (1) initial phase marking the onset of progradation, (2) main phase of large scale outbuilding, and (3) final phase of regional erosion followed by aggradation.

(1) Initial Phase

The initial phase of outbuilding is represented by seismic sequence one (SS1) in the study area, which geometrically seems to be similar to the late Miocene to late Pliocene Molo Formation (Løseth and Henriksen, 2005) in the north and the early Miocene to early Pliocene Utsira Formation (Eidvin et al., 2000; Gregersen et al., 1997) in the south. The stratigraphical position of the Utsira Formation in the central northern North Sea area has been assumed to be equivalent to the Molo Formation in the northern part of the mid-Norwegian shelf (Løseth and Henriksen, 2005). The seismic sequence SS1 mapped in this study is geographically located between the areas of the Molo and the Utsira formations. In the northern North Sea sector of the study area SS1 seems extendable into the Utsira Formation of (Eidvin et al., 2000), but further to the south this linkage is rather questionable.

In order to explain the correlation between SS1 and Molo Formation in the north and Utsira Formation in the south, it is very important to consider the uplift history of southern Norway. The domal uplift of the Norwegian mainland probably started in Late Eocene to Early Oligocene time, which also contributed to uplift of shelf areas. The recognition of domal uplift is based on fission track analysis and its exact starting age has to be confirmed from offshore sedimentary record (Faleide et al., 2002; Gabrielsen et al., 2005).

Second important issue to take into the account is the geometry of the continental margin, which, shows that the continental margin is narrower in the Møre Basin area than in the northern and southern parts. When mainland Norway was uplifted, erosion and clastic debris production increased, and the sediments started to fill in and prograde into the marine basins offshore Norway, giving rise to the Molo Formation in the north and the Utsira Formation in the south. As the continental margin was narrower in the east of Møre Basin and got exposed due to uplift, sediments bypassed parts of this Møre Basin, and were deposited in the eastern parts of the Møre Basin in the form of SS1.

In terms of stratigraphical position, the Molo Formation, the SS1, and the Utsira Formation appear to be similar, as viewed from their sequence stratigraphical positions relative to mapped unconformities (Figure 5-5). However, in lack of exact ages of these units, it is impossible to correlate them chronostratigraphically. Based on the available geological evolution data it can be inferred that these units are related to same geological event of domal uplift of mainland

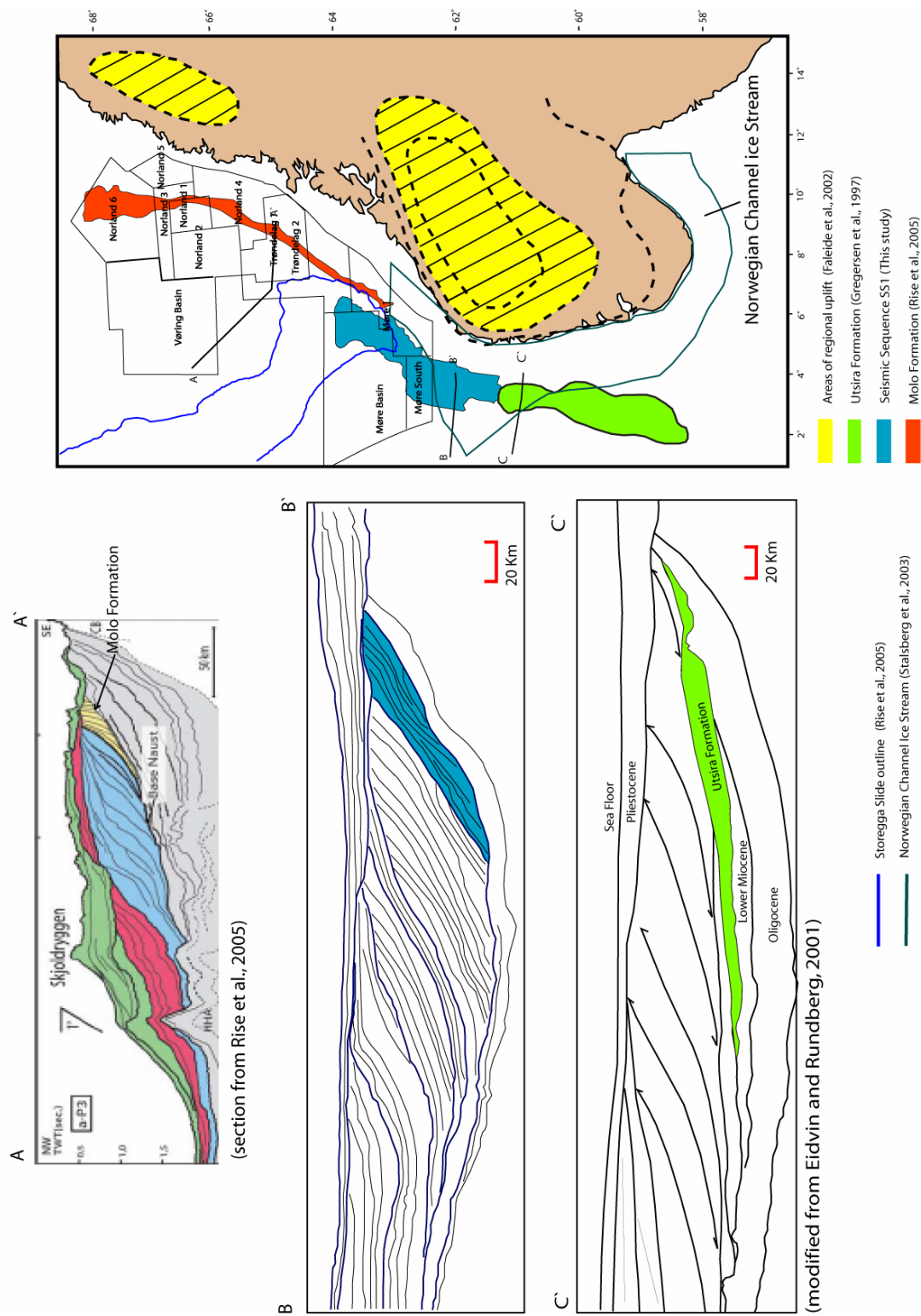


Figure 5-5: Diagram showing the initial phase of large scale progradation evolution in offshore mid-Norway. Submap maps of Molo Formation (Rise et al., 2005), Utsira Formation (Gregersen et al., 1997) together with SS1 are also shown. Seismic section showing the variation in geometry and thickness of seismic sequence SS 1.

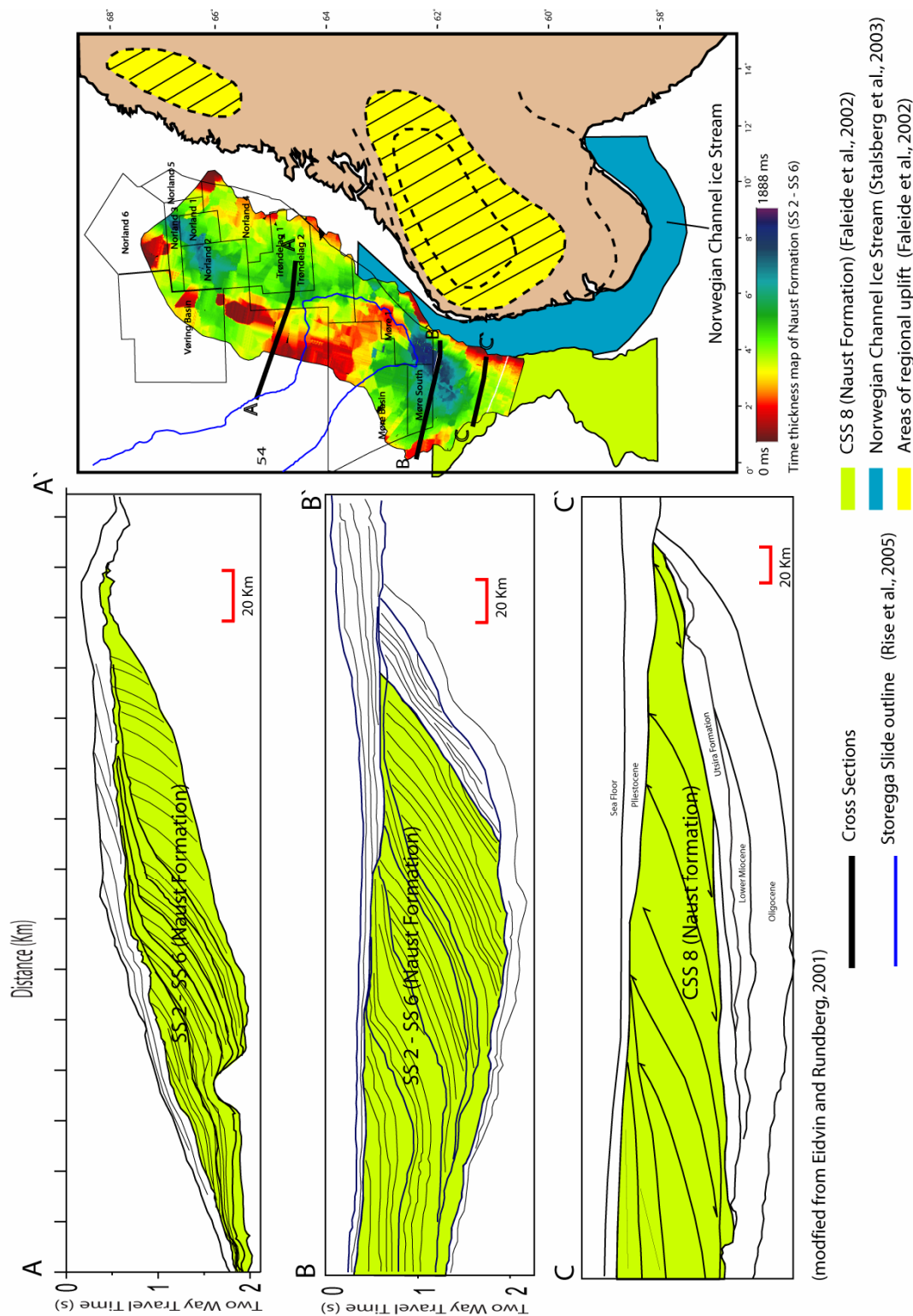
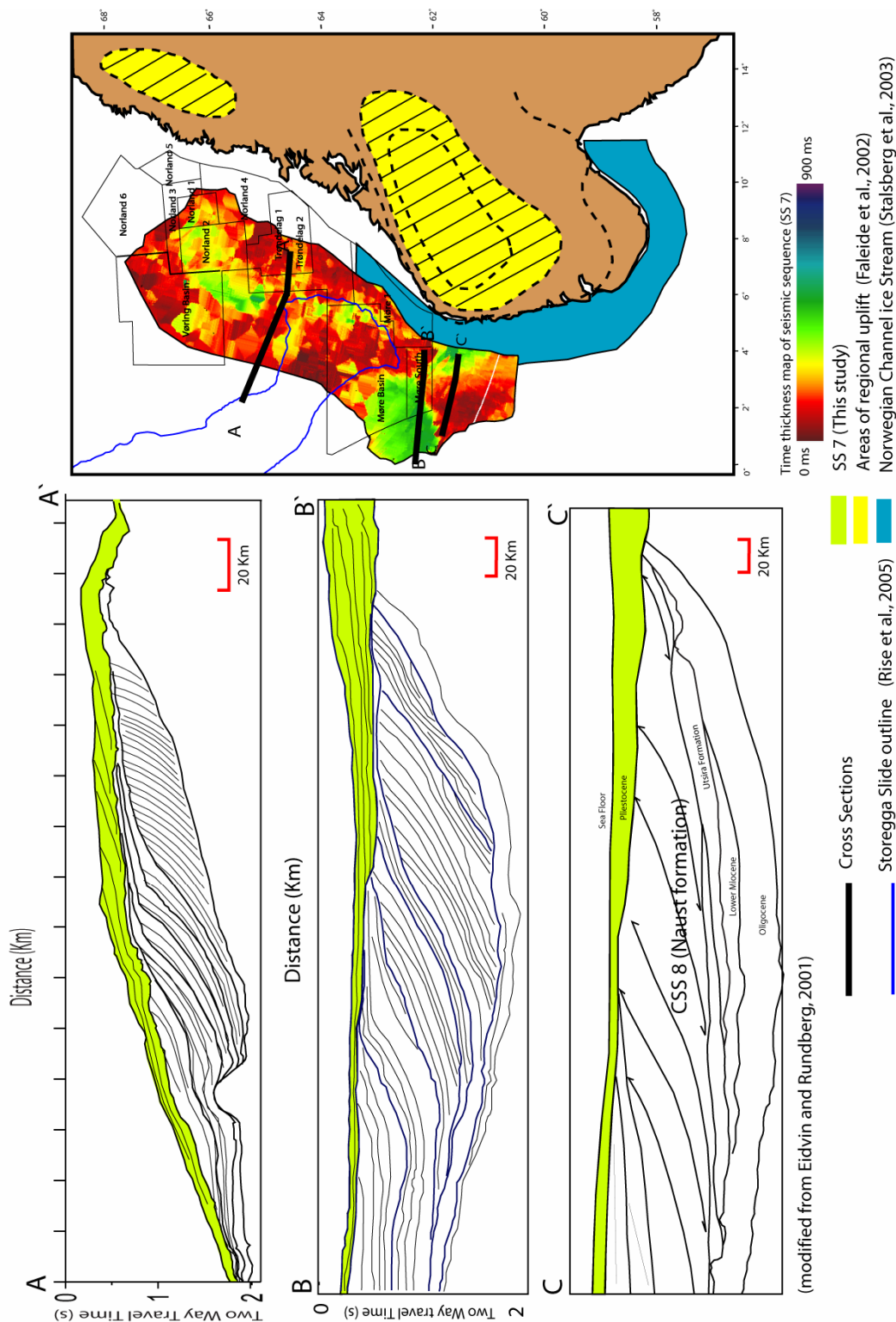


Figure 5-6: Diagram showing the main phase of large scale progradation evolution in offshore mid-Norway. Subcrop maps of CSS 8 Naust formation (Faleide et al., 2002), together with SS2-SS6, are also shown. Seismic section showing the variation in geometry and thickness of seismic sequences SS 2-SS6.



Norway and mark the onset of sediment outbuilding in the northern North Sea and off mid-Norway. Present day settings and position of these units can therefore be attributed to combination of domal uplift of southern Norway and contemporary basin subsidence and creation of accommodation on the Norwegian shelf.

(2) Main Phase-Progradation of the margin and depositional environment

The main phase of large scale progradation is represented by the seismic sequences SS2 to SS6 in the study area. The succession is referred to the Naust Formation in many earlier studies (e.g. Eidvin et al., 1998; Eidvin and Rundberg, 2001; Faleide et al., 2002).

The base of this composite SS2-SS6 unit is marked by a regional downlap surface (RDS) that resulted from enormous sediment outbuilding on it. RDS, which is about 2.7 Ma (Rise et al., 2005) represents more or less similar character in the larger parts of the study area, and represents a relative highstand, a maximum flooding surface (MFS). In the area off Trøndelag platform, there are some indications of little bit erosion along this boundary which makes it a candidate sequence boundary as well. However, in distal parts of the study area the character of RDS is changing from regional downlap surface to conformable surface. So, based on observations in various parts of the study area RDS can be considered as a combination of sequence boundary (SB) and maximum flooding surface (MFS). Erosion in the southern Norway during initial phase stimulated the uplift and tilting and gave rise to more erosion favourable conditions. Tilting (uplift in southern Norway and subsequent subsidence in offshore mid-Norway), resulted from isostatic response to erosion and tectonic uplift, on the other hand, caused subsidence in the basin enhancing geographical relief between sediment source, southern Norway and receiver areas, Møre Basin and surrounding areas (Figure 5-6). Increased uplift and erosion in mainland southern Norway also increased the sediment discharge, whereas increased domal uplift increased tilting of the shelf sediments in the hinge zone between landward domal uplift and oceanward basin subsidence. The flexural subsidence of the marine basin area gave rise to more accommodation space (or increase in relative sea level), that in turn stimulated progradation of the clastic wedge system. Thus, a combination of tilting (uplift onshore, subsidence offshore), erosion, and creation of accommodation space seems responsible for this large scale progradation of siliciclastic sediments off mid-Norway. The enormous sediment supply during the time of deposition of SS2 to SS6 (from 2.7 Ma till 0.4 Ma) have likely resulted from the combination of climatic change into glaciations at the Pliocene / Pleistocene boundary and tectonically triggered

increase in erosion and sediment discharge. Subsidence caused by the tilting in the basins offshore mid-Norway combined with sea level rise seems responsible for creation of required accommodation space in these areas.

Progradation during this second phase (period of deposition of SS2 to SS6) can be divided into two phases based on the geometry of clinoforms. Geometrical pattern shows an early phase with relatively steep clinoforms i.e. from SS2 till SS4. Source area of sediments in the clinothemes seems to be in the north-eastern direction. The second phase consists of gently sloping clinoforms i.e. SS5 and SS6 indicating an eastern source.

In the Haltenbanken–Trænabanken region the palaeo-shelf edge prograded nearly 100 km westwards during the time of the seismic sequence SS2 (Figure 4-6). This corresponds poorly with the suggested environment in the period 2.7–1.1 Ma (‘moderate glaciations/limited degree of ice flow onto the shelf’) inferred by several authors (Henrich and Baumann, 1994; Mangerud et al., 1996; Hjelstuen et al., 1999). Contrary to this assumption, the present sequence stratigraphy appears better supporting the assumption of (Rise et al., 2005) that a large part of the massive, prograding sediment wedge system was formed during numerous ice-sheet advances to the palaeo-shelf edge.

In the Trænabanken/Trænadjupet area, (Henriksen and Vorren, 1996) concluded that the oldest part of the Naust Formation was deposited in a proximal position to grounded ice sheets on the shelf. A fairly high content of angular gravel fragments in the lower part of the Naust Formation has been observed in exploration wells, indicating that a glacial environment on the shelf was common in Late Pliocene time. Boreholes at Haltenbanken show till in the seismic unit IKU-I (Rokoengen et al., 1995), which is a part of SS1.

Some palaeo-shelf surfaces represent erosional unconformities (Figure 4-3 and 4-5) which were formed either by glacial or marine/fluvial erosion. The whole “Naust period” was characterised by sea-level fluctuations; marine erosion, particularly of the inner shelf, was probably intermittently an important process in redistributing sediments westwards. Melt water rivers may have supplied sediments directly to the shelf or shelf break, particularly in the period before the over-deepened fjords were formed. However, the dominant sediment matrix of the Naust Formation is clay/silt, and well logs show only some layers of sand. It is, therefore, unlikely that rivers have contributed substantially to the extensive progradation

during ice-free periods (Rise et al., 2005). On the other hand, seismic facies analysis of the present study shows that there is possibility of having some sand in the bottom sets of SS2 (part of Naust Formation) in the form of shingled clinoforms (see also seismic facies analysis).

In the Møre region and farther south, SS2 and SS3 are thin, possibly indicating that glaciations and deposition from shelf ice sheets were of less importance in southern Scandinavia during the early “Naust period”. During the period represented by the SS4 and SS5, the glacial processes in the southern region became more important than earlier, and the Norwegian Channel Ice Stream probably started to operate in this period (Rise et al., 2005). At the same time, the shelf edge was built out close to its present position (Figure 4-3, 4-4 and 4-5). The ice sheets and ice streams extended out to the entire shelf edge at several times during the last three to four glaciations, and deposited significant volumes of sediment at the margin.

It is difficult to interpret depositional processes directly from the seismic pattern, but hemipelagic and contourite sediments probably make up a small portion of the total sediment volume of this prograding wedge of SS4-SS5, in contrast to the dominance to various down-slope processes. These processes, created by gravity mass instability at the buoyancy line of the grounded ice sheets, may have included debris flows, slides, slumps and turbidity currents. In the Storegga slide area and at the North Sea Fan, parts of the glaciogenic debris deposited on the slope were displaced through several large slide events (Nygård et al., 2005; Solheim et al., 2005).

At the top of the composite SS2-SS6 succession, most of the prograding clinothemes have been truncated as a result of the erosion of their topsets. Advancing ice sheets have been considered as responsible for this erosion. Erosion of topsets of the clinoforms, presence of more or less horizontal toplap truncation, and prograding of parallel clinoforms suggests that deposition and glacial erosion have been complementary processes during this phase.

(3) Final Phase

The final phase in the evolution of large scale sediment outbuilding off mid-Norway is represented in this study by SS7 (Figure 5-7). A distinguished flat lying unconformity termed as URU (upper regional unconformity) marks a major change in stratal architecture and

truncates all underlying prograding units. Over a large area it is overlain by aggrading units that preserves glacial tills and other associated sediments from previous multiple ice-sheet advances and retreats. The development of aggrading and more or less horizontal sedimentary succession marks the end of major uplift in the mainland Norway and therefore also terminations of the large scale tilting of shelf strata. Termination of tilting and uplift is also evident by the relative reduced sediment influx during this final phase. The rate of sediment supply was more or less equal to the rate of creation of accommodation space. Although, in some parts of the Vøring Basin there are some indications of very gentle progradation at this stage but it seems to be more localised phenomena.

Summary and Conclusions

Starting as early as late Miocene, large quantities of sediments were transported westwards from the onshore Norway and inner shelf areas, gradually building out the current shelf during the last c. 2.7 Ma. Maximum recorded thickness exceeds more than 1000 m over extensive areas along the present shelf edge.

The sequence stratigraphic evolution of the Late Cenozoic outbuilding in the northern North Sea and off mid-Norway took place by the formation of seven seismic sequences during three phases: (1) Initial phase marks the onset of sediment progradation with formation of sequence SS 1; (2) Main phase of large scale sediment outbuilding, SS 2 – SS 6; and (3) Final phase of regional erosion followed by aggradation in SS 7.

The Plio-Pleistocene prograding wedge succession formed as response to a complex interplay between a set of diverse controlling factors: tectonics and climate; sediment supply from a variety of sources, primarily glacially derived; sediment transport mechanisms involving downslope and along slope current activity; and deep and shallow water erosional and depositional processes.

The wide shelf in the Haltenbanken-Trænabanken region is mainly a result of extensive progradation of sediment wedges into a basin of intermediate 200-300 m water depth with a gentle seaward dipping basin floor, expanding the shelf 100–150 km westwards. Less sedimentary material was supplied to the Møre shelf, but the narrow shelf in this area is mainly the result of a steeper dip of the pre-existing slope towards a much deeper basin, causing a larger proportion of sediments to be dispersed towards the deep ocean by gravity mass flows.

The sedimentation rate changed through time of deposition, mostly depending on glacial activity and relative sea level changes. In early “Naust time” (SS 2), the most extensive progradation occurred in the Lofoten–Haltenbanken area. The importance of glaciations at the Møre shelf and farther south increased through the Pleistocene period.

The chronostratigraphic data are partly inconsistent. SS 2 - SS 5 is older than 1.1 Ma, and may be more than 2.3 Ma. The two youngest sequences (SS 6, SS 7) probably represent the last c. 400,000 years.

References

- Blystad, P. et al., 1995. Structural elements of Norwegian continental shelf, Part 2 The Norwegian Sea Region. NPD-BULLETIN No.8.
- Brekke, H., 2000. The tectonic evolution of the Norwegian Sea Continental Margin with emphasis on the Vøring and Møre Basins. Geological Society of London, London.
- Bukovics, C., Cartier, E.G., Shaw, N.D. and Ziegler, P.A., 1984. Structure and development of the mid-Norway Continental Margin. In: A.M. Spencer (Editor), North European Margin Symposium. Petroleum Geology of the North European Margin. Graham & Trotman Ltd., Norwegian Institute of Technology (NTH) in Trondheim, Norway, pp. 407-425.
- Bukovics, C. and Ziegler, P.A., 1985. Tectonic development of the Mid-Norway continental margin. *Marine and Petroleum Geology*, 2: 2-22.
- Bullimore, S., Henriksen, S., Liestøl, F.M. and Helland-Hansen, W., 2005. Clinoform stacking patterns, shelf-edge trajectories and facies associations in Tertiary coastal deltas, offshore Norway: Implications for the prediction of lithology in prograding systems. *Norwegian Journal of Geology*, 85: 169-187.
- Coe, A.L. et al., 2003. *The Sedimentary Record of Sea Level Change*. Cambridge University Press, Cambridge, 288 pp.
- Coleman, J.M. and Wright, L.D., 1975. Modern river deltas: Variability of processes and sand bodies. *Deltas - Models for Exploration*. Houston Geological Society, 99-149 pp.
- Dahlgren, K.I.T. et al., 2005. Late Cenozoic prograding wedges on the NW European continental margin: their formation and relationship to tectonics and climate. *Marine and Petroleum Geology*, 22: 1089-1110.
- Dalland, A., Worsley, D. and Ofstad, K., 1988. A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid and northern Norway. *Norwegian Petroleum Directorate Bulletin*, 4: 65pp.
- Doré, A.G., 1991. The structural Foundation and evolution of Mesozoic Seaways between Europe and the Arctic. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 87(1-4): 441-492.
- Doré, A.G., 1992. Synoptic palaeogeography of the Northeast Atlantic Seaway: Late Permian to Cretaceous. *Basin on the Atlantic Seaboard: Petroleum Geology, Sedimentology and basin Evolution*, 62. Geological Society Special Publication, 421-446 pp.
- Ehrenberg, S.N., 1990. Relationship between diagenesis and reservoir quality in sandstones of the Garn Formation, Haltenbanken, mid-Norwegian continental shelf. *American Association of Petroleum Geologists (AAPG) Bulletin*, 74: 1538-1558.

- Ehrenberg, S.N. and Nadeau, P.H., 1989. Formation of diagenetic illite in sandstones of the Garn Formation, Haltenbanken, mid-Norwegian continental shelf. *Clay Minerals*, 24: 233-253.
- Eidvin, T., Brekke, H., Riis, F. and Renshaw, D.K., 1998. Cenozoic stratigraphy of the Norwegian Sea continental shelf, 64°N–68°N. *Norsk Geologisk Tidsskrift*, 78: 125-151.
- Eidvin, T., Jansen, E., Rundberg, Y., Brekke, H. and Grogan, P., 2000. The upper Cainozoic of the Norwegian continental shelf correlated with the deep sea record of the Norwegian Sea and the North Atlantic. *Marine and Petroleum Geology* 17: 579-600.
- Eidvin, T. and Rundberg, Y., 2001. Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on chronology of early Neogene sands. *Norsk Geologisk Tidsskrift*, 81: 119-160.
- Embry, A.F., 1995. Sequence boundaries and sequence hierarchies: problems and proposals. *Sequence stratigraphy on the Northwest European Margin*, Special publication 5. Norwegian Petroleum Society (NPF), 1-11 pp.
- Emery, D. et al., 1996. *Sequence Stratigraphy*. Blackwell Science Ltd., London, 297 pp.
- Evans, D., Stoker, M.S., Shannon, P.M. and Partners, S., 2005. The STRATAGEM project: Stratigraphic Development of the glaciated European margin. *Marine and Petroleum Geology*, 22: 969-976.
- Jordt, H., Faleide, J.I., Bjørlykke, K. and Ibrahim, M.T., 1995. Cenozoic sequence stratigraphy of the central and northern North Sea Basin: tectonic development, sediment distribution and provenance areas. *Marine and Petroleum Geology*, 12(8): 845-879.
- Faleide, J.I. et al., 2002. Tectonic impact on sedimentary processes during Cenozoic evolution of the northern North Sea and surrounding areas. *The Geological Society of London*, 196.
- Gabrielsen, R.H. et al., 2005. Vertical movements in south-western Fennoscandia: a discussion of regions and processes from Present to the Devonian Onshore-Offshore Relationships on the North Atlantic Margin, 12. Elsevier B.V (c) Norwegian Petroleum Society (NPF), Amsterdam, 1-28 pp.
- Galloway, M.E., Garber, J.L., Xijin, L. and Sloan, B.J., 1993. Sequence stratigraphic and depositional framework of the Cenozoic fill, Central and Northern North Sea Basin. *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. The Geological Society, London, 33-43 pp.
- Galloway, W.A., 1989. Genetic stratigraphic sequences in basin analysis I: Architecture and genesis of flooding surfaces bounded deposition units. *American Association of Petroleum Geologists (AAPG) Bulletin*, 73(2): 125-142.

- Gregersen, U., Michelsen, O. and Sørensen, J.C., 1997. Stratigraphy and facies distribution of the Utsira Formation and the Pliocene sequences in the northern North Sea. *Marine and Petroleum Geology*, 14: 893-914.
- Helland-Hansen and Gjelberg, J.G., 1994. Conceptual basis and variability in sequence stratigraphy; a different perspective. *Sedimentary Geology*, 92: 31-52.
- Henriksen, S. and Vorren, T.O., 1996. Late Cenozoic sedimentation and uplift history on the mid-Norway continental Shelf *Global and Planetary Change*, 12: 95-117.
- Henriksen, S. and Weimer, P., 1996. High-Frequency Depositional Sequences and Stratal Stacking Pattern in Lower Pliocene Coastal Deltas, Mid-Norwegian Continental Shelf. *AAPG Bulletin*, 80(12).
- Hollander, N.B., 1984. Geohistory and hydrocarbon evaluation of the Haltenbanken area. In: A.M. Spenser (Editor), *North European Margin Symposium. Petroleum Geology of the North European Margin*. Graham & Trotman Ltd. London, for Norwegian Petroleum Society, Norwegian Institute of Technology (NTH) in Trondheim, Norway, pp. 383-388.
- Jordt, H., Thyberg, B.I. and Nøttvedt, A., 2000. Cenozoic evolution of the central and northern North Sea with focus on differential vertical movements of the basin floor and surrounding clastic source areas. *Dynamics of the Norwegian Margin*. Geological Society of London, London, 219-243 pp.
- Kendall, C.G.S.C. and Lerche, I., 1988. The rise and fall of eustasy. *Sea Level Changes: An Integrated Approach*, 42. Society of Economic Paleontologists and Mineralogists (SEPM), 3-17 pp.
- Knott, S.D., Burchell, M.T., Jolly, E.J. and Fraser, A.J., 1993. Mesozoic to Cenozoic plate reconstruction of the North Atlantic and hydrocarbon plays of the Atlantic margins. *Petroleum Geology of Northwest Europe. Proceedings of the 4th Conference*. Geological Society of London, London, 953-974 pp.
- Løseth, H. and Henriksen, S., 2005. A Middle to Late Miocene compression phase along the Norwegian passive margin. *Petroleum Geology: North-West Europe and Global Perspectives--Proceedings of the 6th Petroleum Geology Conference*. Geological Society, London, London, 845-859 pp.
- Martinsen, O.J., B., F., C., M.A., M. and G., N., A, 1999. Cenozoic development of the Norwegian margin 60–648N: Sequences and sedimentary response to variable basin physiography and tectonic setting. In: B. A.J., S.A.R (Editor), *Petroleum Geology of Northwest Europe*. Geological Society of London, pp. 293-304.
- Miall, A.D., 1986. Eustatic sea level changes interpreted from seismic stratigraphy: a critique of the methodology with particular reference to the North Sea Jurassic record *American Association of Petroleum Geologists (AAPG) Bulletin*, 70: 131-137.
- Mitchum, R.M. et al., 1977. Seismic stratigraphy and global changes of sea level, part 6: Stratigraphic Interpretation of Seismic Reflection pattern in Depositional Sequences

-
- Seismic Stratigraphy - application to hydrocarbon exploration, 26. American Association of Petroleum Geologists (AAPG).
- Neidell, N.S. and Poggiagliolmi, E., 1977. Stratigraphic modelling and interpretation-Geophysical principles and techniques. Seismic stratigraphy-applications to hydrocarbon exploration., 26. American Association of Petroleum Geologists (AAPG), , 389-416 pp.
- Nygård, A., Sejrup, H.P., Haflidason, H. and Bryn, P., 2005. The glacial North Sea Fan, southern Norwegian margin: architecture and evolution from the upper continental slope to the deep-sea basin. *Marine and Petroleum Geology*, 22.
- Nystuen, J.P., 1998. History and development of sequence stratigraphy. . Sequence stratigraphy - concepts and applications, 8. Norwegian Petroleum Society (NPF), 31-116 pp.
- Payton, C., 1977. Seismic stratigraphy-Applications to Hydrocarbon Exploration, Memoir 26. American Association of Petroleum Geologist (AAPG).
- Pedersen, L.E., 1998. Cretaceous sediment infill in the southern Vøring Basin. Cand. Scient thesis in applied geophysics Thesis, University of Oslo, Oslo.
- Pitman, W.C., 1978. Relation between eustacy and stratigraphic sequences of passive margins. *Geological Society of America, Bulletin* 89: 1389-1403.
- Poole, D.A.R. and Vorren, T.O., 1993. Miocene to Quaternary palaeoenvironments and sedimentary evolution on the mid Norwegian Shelf. *Marine Geology*, 115: 173-205.
- Posamentier, H.W., Jervey, M.T. and Vail, P.R., 1988. Eustatic controls on clastic deposition. I. Conceptual framework. *Sea Level Changes—An Integrated Approach*, 42. SEPM Special Publication, 110-124 pp.
- Praeg, D. et al., 2005. Episodic Cenozoic tectonism and the development of the NW European 'passive' continental margin. *Marine and Petroleum Geology*, 22: 1007-1030.
- Rise, L., Ottesen, D., Berg, K. and Lundin, E., 2005. Large-scale development of the mid-Norwegian margin during the last 3 million years. *Marine and Petroleum Geology*, 22: 33-44.
- Rokoengen, K. et al., 1995. Upper Cenozoic stratigraphy on the mid-Norwegian continental shelf. *Norsk Geologisk Tidsskrift*, 75: 88-104.
- Sangree, J.B. and Widmier, J.M., 1977. Seismic stratigraphy and global changes of sea level, part 9: Seismic Interpretation of Clastic Depositional Facies Seismic Stratigraphy - application to hydrocarbon exploration, 26. American Association of Petroleum Geologists (AAPG), 165-184 pp.
- Shanley, K.W. and McCabe, P.J., 1994. Perspectives on the sequence stratigraphy of continental strata. *American Association of Petroleum Geologists (AAPG) Bulletin*, 78(4): 544-568.
-

- Skogseid, J., Pedersen, T. and Larsen, V.B., 1992. Vøring basin: subsidence and tectonic evolution. Structural and Tectonic Modelling and its Application to Petroleum Geology. NPF Special Publication, 1. Norsk Petroleumsforening (NPF) 55-82 pp.
- Solheim, A., Berg, K., Forsberg, C.F. and Bryn, P., 2005. The Storegga Slide complex: repetitive large scale sliding with similar cause and development. Marine and Petroleum Geology, 22.
- Stoker, M.S. et al., 2005. Neogene stratigraphy and the sedimentary and oceanographic development of the NW European Atlantic margin. Marine and Petroleum Geology, 22: 977-1005.
- Summerhayes, C.P., 1986. Sea level curves based on seismic stratigraphy: their chronostratigraphic significance. Palaeogeography, Palaeoclimatology, Palaeoecology, 57: 27-42.
- Vail, P.R., 1987. Seismic stratigraphy interpretation using sequence stratigraphy. Part 1: Seismic stratigraphy interpretation procedure. Seismic Stratigraphy Atlas, 27. American Association of Petroleum Geologists (AAPG), 1-10 pp.
- Vail, P.R. et al., 1977. Seismic stratigraphy and global changes of sea level Seismic stratigraphy-Applications to Hydrocarbon Exploration, 26. American Association of Petroleum Geologist (AAPG), 49-212 pp.
- Weimer, P., 1990. Sequence stratigraphy, facies geometries, and depositional history of the Mississippi fan, Gulf of Mexico. American Association of Petroleum Geologists (AAPG) Bulletin, 74: 425-453.
- Wessel, P. and Smith, W.H.F., 1995. Generic Mapping Tool (GMT), New version of Generic Mapping Tools release editor
School of Ocean and Earth Science and Technology (SOEST), Honolulu.
- Wagoner, V.J.C. et al., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. Sea-level Change: An Integrated Approach, 42. Society of Economic Paleontologists and Mineralogists (SEPM), 39-45 pp.
- Whitley, P.K., 1992. The Geology of Heidrum - A Giant Oil and Gas Field on the Mid-Norwegian Shelf. AAPG Memoirs, 54: 383-406.
- Worsley, D. and Aga, O.J., 1986. The Geological History of Svalbard, Statoil, Stavanger.
- Ziegler, P.A., 1982. Geological Atlas of Western and Central Europe. Elsevier, Amsterdam.